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Prescribed Burning Guidelines For Ponderosa Pine in North Idaho

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A Final Report:

Prescribed Burning Guidelines for Ponderosa Pine in North Idaho

By
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and
Leon F. Neuenschwander

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Prescribed Burning Guidelines for Ponderosa Pine in North Idaho

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ABSTRACT

Forty-eight prescribed understory burns were conducted in mature Pinus ponderosa stands of the Pseudotsuga menziesii/Physocarpus malvaceus habitat type during the fall of 1978. These included 15 backfires, 16 strip headfires, and 17 single headfires. Prediction models for fuel reduction, fire behavior, and overstory damage were developed from pre-burn fuel and weather data using a forward stepwise multiple regression procedure. Dependent variables for fuel reduction included litter, duff, litter plus duff, four size classes of woody fuel, all woody fuel, and total fuel. Fire behavior dependent variables included flame length, rate of fire spread, flame residence time, and crown scorch height. The regression models were in two parts, 1) all burn treatments combined; and 2) separated by burning method. Analysis of covariance with a protected Least Significant Difference showed that fuel reduction was not dependent on burning method. However, fire behavior of backfires differed significantly from that of both types of headfires. Percent of area burned was significantly affected by amount of disturbance, thereby implying that heavily disturbed areas may preclude the use of backfires. Results indicated that prescribed understory burning had applications for a variety of objectives such as wildlife habitat manipulation, site preparation, precommercial thinning, and wildfire risk abatement.

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INTRODUCTION

The Bureau of Indian Affairs and other land management agencies have been conducting uneven-aged management in the Douglas-fir/ ninebark (Pseudotsuga menziesii/Physocarpus malvaceus) habitat type with seral ponderosa pine (Pinus ponderosa) as the preferred commercial species. On site natural fuel accumulation combined with unmerchantable logging residue made some form of fuels management necessary to reduce potential wildfire damage to crop trees (Martin and Brackebusch 1974). Fuels manipulation practices included mechanical and hand piling, pile burning, and broadcast burning.

Some disadvantages of the first two practices were soil disturbance and compaction caused by heavy machinery, especially crawler tractor vehicles (Garrison and Rummell 1951, Seidel 1974), and soil structure breakdown under burned piles caused by intense prolonged heat (Fuller et al. 1955, Seidel 1974). Also, hydrophobic chemicals could be introduced into the soil (Zwolinski 1980). Fuel reduction was primarily in large woody fuels with mechanical piling, and small woody fuels with hand piling. There was also the problem of soil being introduced into mechanically produced piles (Jemison and Lowden 1974). Finally, the cost of mechanical piling was high and unrelated to the size of the treatment area.

Prescribed understory broadcast burning for fuels management in this habitat type had none of the above disadvantages. Ground machinery was not required for the fuels management phase of broadcast burning, so no soil compaction or disturbance occurred. Because there were no large artificial accumulations of fuel, heat release was dispersed over a large area and soil degradation was minimized (Seidel 1974). Tarrant

(1956) found that understory burning in ponderosa pine forests was not hot enough to consume the humus, incorporated in the mineral soil. Broadcast burning reduced fuels in all categories. Fuel reductions in the litter and duff layers were especially important as these fuels were the primary carrier of the flaming front (Martin and Brackebusch 1974). Significant reduction in the fuels was very effective in lowering the risk of wildfire damage over the entire treatment area (Weaver 1959, 1967). Finally, the cost of broadcast burning was lower than piling and burning, and the cost per acre decreased as the size of the treatment area increases.

The purpose of this research was to determine whether controlled broadcast prescribed burning could be used to meet silvicultural objectives without additional fuel management activities, and the necessary fire parameters needed for such silvicultural prescriptions. The objectives of this research were:

1. To quantify the tool of prescribed understory burning by developing prediction models for fire behavior (rate of fire spread, flame length, and residence time) and fire effects (fuel reduction and crown scorch height) based on preburn measurements of fuel loading, fuel moisture, and weather;

2. to test for differences in fire behavior and effects caused by ignition techniques of backfires, free-running headfires, and strip headfires;

3. to ascertain the effects of dead surface fuel accumulations and living aerial fuels on the crown scorch height;

4. to identify the effects of fuel bed disturbances on the completeness of the burn;

5. to determine tree mortality directly caused by burning.

Burning is not a definitive term. Studies indicated that ignition technique was a dominant factor in both the behavior of the fire and its effects on the vegetation. Fahnestock and Hare (1964) found that back-

fires and headfires were equally damaging to the tree cambium at ground line. However, headfires were considerably hotter than backfires on the boles of pine trees. They also noted that tree crowns were more easily killed by headfires than backfires. Backfires appeared to be the safest, least destructive technique. Furthermore, land managers have dealt primarily with highly disturbed forest stands following logging. There have been no studies concerning the different fire behavior and effects in stands where fuel discontinuity was present.

Season of the year was important to the option of prescribed understory burning. Fall burning was preferred to spring or summer burning for several reasons. Spring burning occurred during the most active growing period for all plants. Carbohydrate reserves of the plants were lowest at this time, decreasing the plant's ability to recover from damage (Wagner 1961, Norum 1975). In addition, crown damage was more severe in spring and early summer burning due to the low foliar moisture content and the succulent nature of the buds and twigs (Wagner 1961, Norum 1975). Spring and early summer burning also carried the risk of holdover fires continuing into the drier late summer and fall (Norum 1975). Fall burning usually succeeded in consuming more fuel, especially in the duff and large woody categories which had dehydrated over the summer (Brackenbusch 1975) and was more cost effective in terms of fuels management (Norum 1975). Bark beetles were able to concentrate on damaged trees following early season burns. However, following dormant season burns, insects could not respond to the stressed conditions of the damaged trees until the following spring, which allowed surviving trees additional recovery time (Miller and Keen 1960).

Prescribed understory burning in mature ponderosa pine forests has been used to accomplish a wide variety of objectives in forest land management. Kayall (1974) summarized some of the general objectives of prescribed burning as follows:

1. removal of unpalatable growth remaining on plants from previous seasons;
2. control or destruction of insects and disease;
3. control encroachment of undesirable plants and encourage desirable food plants;
4. aid in distribution of animals over a management unit;
5. removal of naturally accumulated or man-caused fuels;
6. preparation of seedbed for natural regeneration or planting;
7. establishment of fire breaks in a wildfire protection system.

These objectives and others including watershed management and fertilization have been attempted by prescribed burning for ponderosa pine management.

Morris and Mowat (1958) used understory burning to thin a densely stocked stand of ponderosa pine saplings in Washington. Density was reduced from 2410 stems per acre to 895 stems per acre with one application of fire. They noted an increase in both diameter and height growth of the crop trees in the burned area compared to the unburned control. Weaver (1967) reported on this same area after it had been treated with understory burning three times (1942, 1958, 1964). In 1965, the burned area had fewer crop trees per acre than the unburned control (46.0/ac. versus 65.0/ac., respectively). However, crop trees in the burned area were larger than those in the unburned. Ponderosa pine in the former area averaged 7.5 in DBH and 40.7 ft tall, while in the latter they averaged 6.2 in DBH and 35.2 ft tall. Weaver (1959) noted that prescribed burning often produced a spottier and rougher job

of thinning than mechanical means. However, the cost of the former was considerably less.

Understory burning was used to prepare a site for natural regeneration in a shelterwood pine stand in California (Schultz and Biswell 1959). Results from using fire as a site prep tool were not as good as those obtained by mechanical means. However, mechanical site preperation was more expensive.

Biswell et al. (1973) stated several ways that prescribed understory burning was used to reduce wildfire risk. Volume of dead fuels was reduced, understory saplings and shade tolerant tree species were thinned or removed, level of green foliage of crop trees was raised through needle scorch and subsequent natural branch pruning, and aerial dead fuels and live shrubs were reduced in height so needle cast was more likely to fall to the ground. Burning in a mosaic pattern over the landscape created fire breaks (Kayall 1971), thereby segregating unburned high risk areas. Biswell et al. (1973) recommended a prescribed burning frequency of 5-7 years to maintain a low risk situation. This frequency depended on the rate of fuel accumulation, particularly of fine fuels as suggested by Norum (1975). Weaver (1955) showed that prescribed burning reduced the risk of wildfire damage. For three seasons following controlled understory burning at Fort Apache, the number of wildfires was reduced by 84%, area burned by wildfires by 91%, and average wildfire size by 65%. At the Colville Indian Reservation, wildfires were examined for 12 seasons following prescribed burning treatments (Weaver 1957). There was a 90% reduction in the area burned by wildfire, 94% reduction in damage, and 79% reduction in cost of control per wildfire.

Fuel reduction was the primary means of reducing wildfire risk. Sweeney and Biswell (1961) obtained a 75.9% litter reduction and a 22.9% duff reduction averaged from four burns in California. Hough (1968) found that total fuel reduction in a gallberry-palmetto understory of longleaf-slash pine forests of the southeastern United States was similar for both backfires and headfires (56% and 55%, respectively).

Prescribed burning had other attributes that at times were the focus of the objective for treating an area with fire. For example, burning has been used to alter watershed runoff characteristics. Burning for increased water yields required, in most cases, a fire which removed most of the protective water absorbing organic material (i.e., litter and duff), but still left enough to prevent or effectively reduce the potential for erosion (Zwolinski and Ehrenreich 1967). Davis et al. (1968) conducted prescribed burns on Arizona watersheds in ponderosa pine for the purpose of increasing water yields. The objective was to remove 75% of the 2 to 3-inch duff layer. Also accomplished was basal area thinning, increased seedling germination, and reduction in wildfire hazard. However, after two years of fuel accumulation following the fires, the wildfire hazard had almost returned to preburn levels.

Partial consumption of organic matter by fire resulted in release of many bound nutrients and enhanced fertilization. Fuller et al. (1955) found that controlled burning temporarily increased soil fertility. Rain leached the released soluble salts into the remaining duff and mineral soil. Phosphorus, in particular, and sodium, calcium, and potassium were made available to plants at the three Arizona burns. Vlamis et al. (1955) demonstrated an increase in the available nitrogen that was directly related to the severity of the burn, but inversely

related to the time elapsed after burning. The effect was most dramatic in the 8 inches of surface soil. Phosphorus levels were increased as a result of burning in only the Holland soil type. The other soil type (the Salminas soil) is a phosphate fixing type. Wagle and Kitchen (1972) found that the available nitrogen and phosphorus increased in the surface 15 cm of soil for three years after burning. This effect decreases with time after ignition.

Vegetation manipulation by prescribed understory burning was complex. Plant response to burning in terms of the individual or the progeny was dependent upon 1) time of the burn in relation to the species life form and phenology; 2) intensity of the burn; 3) soil moisture during and following the burning; 4) site characteristics and potential; and 5) management activities before the burn. Ecosystem manipulation with fire demanded a clear set of objectives and a precise prescription for burning. The majority of shrub species in the ponderosa pine/larch/ Douglas-fir type were well adapted to fire and resprout vigorously (Wright 1978).

Animal species responded to such changes in environment as food, nesting sites, cover, predator susceptibility, etc. Prescribed burning was used to alter many of these conditions. Bendell (1974) wrote a generalized view of the effects of fire on birds and mammals. The only direct effect was death by asphyxiation and burning of creatures present on the site at the time of the burn. Among the many indirect effects were alteration of the microclimate, including temperature, relative humidity, wind, rain, and snow cover; changing of the vegetational structrue affecting access, reproductive requirements, pattern of plant cover, food and water availability. Ahlgren (1974) concluded that with

the exception of mesofaunal species and spiders, arthropod reductions by fire were caused by post fire changes in the environment, not by fire's heat.

Prescribed understory burning carried the risk of damage to overstory trees. The cause of the damage was accumulated heat which was sufficient to consume or dessicate the living tissue. The location of the heat source and duration and intensity of fire in relation to living tissue were primary features affecting the overstory. For example, the leaves of trees were the most susceptible to heat damage. However, these tissues were located quite far from the ground heat source. The cambium existing at the base of the tree stem might have been quite insulated from the heat, but was very close to it. The literature verified that these two locations were primary places where tissue damage occurred during fire (Martin and Brackebusch 1974, Van Wagner 1973).

Accumulated heat necessary to kill plant tissue was a time-temperature relationship; a high temperature exposure for a short period of time, or a lower temperature exposure for a long time period. Kayll (1968) and Hare (1961) reported that conifer foliage was killed by a one minute exposure to 60°C or a ten minute exposure to 50°C. The lethal temperature may vary due to foliar moisture content changes which affected specific heat changes of needles throughout the growing season. In Douglas-fir this accounted for a 15% change in specific heat of the needles, which Van Wagner (1973) considered insignificant, but which might be significant in ponderosa pine.

The height at which lethal foliage temperature was reached or exceeded above a flaming front was dependent upon fire intensity,

ambient air temperature, and wind speed. The basic theoretical models for prediction of scorch height were given by Taylor (1961) and Thomas (1964). Equation one related scorch height to the 2/3 power of fire line intensity (I). Equation two involved the intensity and the ambient air temperature (T) in degrees Centigrade. The third equation introduced the wind (W) as a variable. Van Wagner (1973) adapted these equations for low wind conditions.

$$h_s = 0.385\ I^{2/3} \qquad \text{Equation 1}$$

$$h_s = \frac{11.61\ I^{2/3}}{(60 - T)} \qquad \text{Equation 2}$$

$$h_s = \frac{3.94\ I^{7/6}}{\sqrt{0.107\ I + U^3}\ (60-T)} \qquad \text{Equation 3}$$

Van Wagner (1973) obtained close correlation of these models to his data in Douglas-fir stands in Vancouver, B.C. However, he admitted that the range of his data was very limited.

Wind speed was a variable that was difficult to ascertain because of its effect upon several aspects of fire behavior. As the wind speed increases, the convection column is deflated. Cooler air entrains into the plume, and the effective distance to the crown canopy is increased. This would tend to reduce the temperature at any vertical height above the ground. However, wind speed also increased the fire line intensity by increasing the combustion rate, thereby increasing the temperature in the convective plume. Van Wagner (1973) suggested that the latter effect is dominant. Therefore, the scorch height increases as the wind speed increases (above his data range = 2-3 MPH).

Silen (1974) found that damage to the cambium was a result of fire temperature, the exposure time, and the bark thickness. Fahnestock and Hare (1964) conducted studies on flame temperatures during understory burning. They found 1) temperatures were always greater on the leeward

side of the stem from the wind; 2) maximum temperatures occurred at tree bole ground line in backfires on both sides of trees, whereas in headfires maximum temperature was at ground line on the windward side, but from one to three feet above ground on the leeward side; 3) backfires were as hot as headfires at ground line; and 4) backfires and headfires contributed essentially the same amount of total heat to the cambium on the leeward side. This suggested that the most likely position on the tree bole for cambium damage was at the ground line or just above it. However, this position was also where the bark thickness was greatest.

Ponderosa pine outer bark is a thick, low density exfoliating material with a relatively low moisture content that does not conduct heat readily. The bark surrounds a very moist core of high density wood which is thermally conductive. The outer bark insulates the cambium from external heat, and the cambium tends to dissipate the heat energy it receives. Martin (1963) claimed that these factors favored survival of cambium in large diameter trees because the bark was thicker and the internal moist wood volume was much greater than in small diameter trees.

Most researchers considered foliar damage to be more important than cambial damage to the trees survival. Trees must be completely girdled to be killed by cambial damage alone. Any fire hot enough to have girdled a large tree was usually intense enough to scorch all of the foliage as well (Van Wagner, 1973). Wagener (1961) also indicated that crown damage was more important (Table 1). However, he claimed that the amount of live crown remaining after a fire was the best predictive factor. Live crown was not the amount of green crown left,

Table 1. Criteria for survival marking of fire-scorched timber in California.[1]

Influencing factors	Minimum criteria for survival of Ponderosa pine Jeffrey pine		
	Cambium injury	Live crown	Green foliage
General specifications		Percent	
Fire period—late season Site quality—above average Growth vigor of tree before fire—good	None or light	50 or more	10 or more[2]
Modifications			
In cambium injury—general specifications as above	Moderate	50 or more	20 or more
In site—below average, Sierra East Side and West Side, other general specifications unchanged	None or light	50 or more	15 or more
In fire period—midseason other general specifications unchanged	None or light	50 or more	15 to 25 or more
In growth vigor—crown small, vigor moderate, other general specifications unchanged	None or light	60 or more	15 or more

[1] Taken from Wagener (1961).

[2] Not an actual green foliage minimum for survival. Seventy percent of the pine in the study with 50 percent or more of live crown but with less than 10 percent of green foliage survived.

but the percent of live twigs, buds and needles. Minimum criteria for survival of ponderosa pine in fall sites on good sites were less than 90% crown scorch, less than 50% crown kill, and little cambial damage. Headfires tended to be more damaging than backfires (Fahnestock and Hare 1964). All trees in their headfire plots had some crown scorch (up to 100%) and cambial damage. However, none of the trees in the backfire plots had crown scorch or detectable cambial damage.

Damage to crop trees by fire also involves the plants, ability to recover from unfavorable microclimatic conditions, and resist invasion by insect and disease. Miller and Patterson (1927) found that fire-damaged ponderosa pine with greater than 50% loss of their foliage were most often attacked by bark beetles. Miller and Keen (1960) felt that the subsequent tree mortality was due to the aggregation of the beetles from the surrounding area rather than a local population buildup. Mitchell and Sartwell (1974) felt that prescribed understory burning could be conducted without threat of Dendroctonous brevicomis attack, provided the trees are not seriously damaged by the fire. A concurrent study was conducted at two of the locations of this research to determine the short-term response of bark beetles to prescribed burning (Chatelain et al. in prep). They found that burning increased the incidence of bark beetle attack (species include Ips pini, Dendroctonous valens, and D. brevicomis). The differences between total attacks of ponderosa pine were significant only between the free-running headfires and the no-burn controls ($p \leq .05$).

There has been no research conducted on the disease-prescribed burning interaction. Pathogens may be introduced to the trees via fire scars or indirectly with bark beetle and wood borer activity.

Damage to site quality was another important consideration in prescribed understory burning. Erosion was the primary damage caused by burning; it increased in direct proportion to the severity of the burn. Severe fires, whether prescribed or wildfire, killed overstory plant cover, removed all or part of the duff layer, consumed part of the incorporated soil and reduced the soil's ability to absorb moisture quickly, thus causing erosion. Obviously, a planned understory fire of this nature was too hot to accomplish all burn objectives. None of the reviewed publications obtained 100% vegetation mortality or 100% litter-duff removal for any individual prescribed fire (Fahnestock and Hare 1961, Sweeney and Biswell 1961, Davis et al. 1965, Hough 1968, Norum 1975).

Soil properties altered by burning included: 1) increased macroscopic pore volume, decreased microscopic pore volume, but no change in total pore volume; 2) no change in incorporated humus quantity; 3) increased water repellency of the mineral soil particles; 4) increased water yield and sedimentation; and 5) decreased permeability coefficient (cm/h) (Fuller et al. 1955, Tarrant 1956, Campbell et al. 1977). The findings of these researchers and others have varied depending upon soil type and severity of the burn, frequently with contradictory results. Moore and Norris (1974) concluded that repeated understory burning in the Southeast had no deleterious effect on chemical or physical soil properties, and did not decrease soil productivity. They also felt that this general conclusion applied to the Pacific Northwest.

Prescribed understory burning has been used to accomplish the aforementioned objectives under a wide variety of conditions. Fuel loadings ranged from 300 lb/acre to 300 ton/acre. Fuel moisture

contents ranged from 7-20% in the fine fuels and 8-14% in the 10 h timelag fuels. Weather conditions also varied considerably: 1) air temperature, 7 - 27°C (20-80°F); 2) surface wind speed, 0-15 mph; and 3) relative humidity, 10-60%. Ideal burning conditions for any given objective were achieved with compensating factors of low fuel loadings with flammable conditions, or high fuel loadings with cool, moist conditions (Neuenschwander 1978). Optimum burning conditions in heavy fuels were summarized by Wright (in prep. a). Air temperature ranged from 4-16°C (40-60°F), relative humidity, 25-40%, understory wind speed, 2-7 mph, and a 10 h timelag fuel moisture stick reading greater than 15%. Backfires with strip headfires were the preferred ignition pattern in heavy fuels. Wright (in prep. b) also summarized Biswell's procedure for burning in light fuels. Conditions were as follows:

1) air temperature, 16-21°C (60-70°F);
2) wind speed, 4-5 mph;
3) relative humidity, 25-40%; and
4) 10 h timelag fuel moisture sticks, 7-10%.

Light fuels offer more flexibility or ignition techniques than the heavy fuels.

Each objective was accomplished under a restricted set of conditions of fuel and weather. More than one objective was satisfied by one application of controlled burning, although the conditions might have to be compromised.

Neuenschwander (1978) suggested that a standard set of measurements should be taken at each burn to facilitate comparison of fire behavior and fire effects. The weather parameters of air temperature, relative humidity, and wind speed were stated in most research burn reports.

However, total fuel loading as well as the fine fuel categories should be sampled preburn. The moisture contents of the litter, duff, 1 h, 10 h were also important. During the burn, fire intensity and burnout time were necessary for the prediction of postburn vegetation response. Rate of fire spread was necessary for fire control purposes and crown scorch height was important to tree response. Neuenschwander also stated that postburn conditions needed to be evaluated more conclusively. Objectives of the research were usually presented. However, the degree of success to which the burning accomplished those objectives was frequently omitted.

One of the most valuable pieces of research relating preburn conditions to postburn effects was done by Norum (1975) in western larch-Douglas-fir forests of Montana. He generated models for the prediction of fuel reduction in several type and size categories as well as for fire intensity, temperature penetration into the soil, and cambial death. The predictor variables were the preburn measurements of fuel loading, fuel moisture, and weather conditions. Norum's work formed the basis for this research, and many of his equations and conclusions will be compared to the findings of this study.

Davis et al. (1968) presented a prescription for consuming duff on Arizona watersheds as follows: 1) air temperature, greater then 24° C (75° F); 2) wind, 2-5 mph; 3) weather, clear skies; 4) fuel temperature averages 21° C (80° F); 5) upper duff moisture content, 6-12%; and 6) lower duff moisture content, greater than 15%. The ignition technique was flank fires at 10 to 20 feet spacing.

Hough (1968) conducted understory burning in slash and longleaf pine forests to study fire behavior and fuel consumption. He estimated litter reduction and fuel energy output in backfires from the dry weight

and moisture content of the litter layer. Also, the rate of spread of backfires was inversely related to the moisture content of the fresh litter layer. Furthermore, the spread rate did not change for ground wind speeds less than 8 mph (13 mph).

SITE DESCRIPTION

This study was conducted on land owned or managed by the Coeur d'Alene Indian Tribe/Bureau of Indian Affairs in Benewah and Kootenai counties of northern Idaho (Figure 1). Four locations were selected in mature, seral ponderosa pine (Pinus ponderosa) stands of the Douglas-fir/ninebark (Pseudotsuga menziesii/Physocarpus malvaceus) habitat type as described by R. and J. Daubenmire (1968). Two of the research areas located near Tensed, Idaho, supported a mixed stand of ponderosa pine with occasional Douglas-fir. These were selectively harvested during the summer of 1978, just prior to burning (Tables 2 and 3). The remaining sites, one near Plummer, Idaho, and the other near Worley, Idaho, consisted of pure ponderosa pine stands surrounded by agri cultural land. Both of these sites were selectively harvested prior to 1975 (Finan, pers. comm.).

The understory vegetation was locally dominated by a mixture of shrubs characteristic of the ninebark union (Daubenmire 1968). However, the low rhizomatous shrubs of snowberry (Symphoricarpos albus) and wild rose (Rosa spp.) had a greater cover. Native and introduced grasses were abundant. The most common grasses were pine grass (Calamagrostis rubescens), wild rye (Elymus glaucus), and Kentucky grass (Poa pratensis). A diverse mixture of forbs was conspicuously present; however, their cover was low.

Figure 1. Location of study sites.

Table 2. Basal area (m^2/ha) for all conifers by location measured at breast height, 4.5 ft.

Location	*Pinus ponderosa*	*Pseudotsuga menziesii*	*Abies grandis*	*Larix occidentalis*
Tensed 1	14.14 c[1]	4.83 a	0.00	0.10
Tensed 2	25.01 b	0.60 b	0.14	0.00
Worley	26.20 b	0.00 b	0.02	0.00
Plummer	37.48 a	0.00 b	0.00	0.00

[1] Means for each species followed by different letters are significantly different at $p < .05$.

Table 3. Tree stem density (no./ha) for all locations of *Pinus ponderosa* and *Pseudotsuga menziesii*.

DBH (cm)	Tensed 1		Tensed 2		Worley	Plummer
	P pine	*D-fir*	*P pine*	*D-fir*	*P pine*	*P pine*
0-5	564	192	870	9	–	427
5-10	128	26	167	9	10	10
10-15	67	21	74	4	39	33
15-20	31	3	80	2	47	13
20-25	13	8	52	2	55	15
25-30	18	8	33	–	33	13
30-35	3	8	13	–	29	19
35-40	10	–	20	–	31	29
40-45	3	3	20	2	20	38
45-50	3	3	9	–	20	19
50-55	8	3	9	–	18	27
55-60	3	–	6	–	4	25
60-65	8	3	–	–	–	8
65-70	3	–	4	–	–	8

The soils of the Tensed units were classified as loamy skeletal, mixed, frigid Dystric Xeroochrept of the Minaloosa series. The Plummer site was a fine-silty, mixed, mesic argiaquic Xeric Argialboll of the Southwick series. The Worley site had two soil types. The lowland positions had the same soil as the Plummer unit. The high ground consisted of fine, montmorillonitic, mesic Mollic Palexeralfs of the Worley series (U.S. Soil Conservation Service, St. Maries, Idaho). All locations were relatively flat with slope gradients ranging from 0 to 30%. Elevations above mean sea level ranged from 790 m (2568 feet) at the Worley unit to 880 m (2860 feet) at both Tensed units.

Mean annual precipitation at the Tensed units was 66cm (26 inches). The mean annual precipitation for both the Worley and Plummer sites was estimated at between 56 and 64 cm (22-25 in.) Air temperature averaged 6.9° C (44.5° F) at the nearest weather station, Tensed, Idaho (U.S. Dept. of Commerce 1976-1978). Annual precipitation measured at this station for 1978 was 69.6 cm (27.4 in.). Although long-term averages were not kept at Tensed, the annual precipitation for the entire north Idaho area was 14% below normal in 1978. It is significant that this same area had below average precipitation for 1977 and 1976 (16% and 20% below normal respectively). The trees may have been under drought stress at the time of the burn.

Fuel loadings on the four locations ranged from 35,090 kg/ha (15.7 t/acre) at Tensed 1 to 58,200 kg/ha (26.0 t/acre) at the Plummer unit (Table 4). The partially decomposed duff was the dominant fuel component on all sites, constituting between 50 and 59% of total fuel loading of any site.

Table 4. Preburn fuel loadings by location (metric t/ha).

Fuel		Tensed 1	Tensed 2	Worley	Plummer
Herbaceous	10^3 kg/ha	0.48	0.39	0.44	0.53
	%	1	1	1	1
Shrubs*	10^3 kg/ha	0.23	0.37	0.54	0.68
	%	1	1	1	1
Litter	10^3 kg/ha	4.04	3.88	3.26	3.49
	%	12	11	6	6
Duff*	10^3 kg/ha	17.57	19.42	33.73	34.40
	%	50	53	58	59
1 Hour	10^3 kg/ha	0.53	0.71	0.59	0.45
	%	1	2	1	1
10 Hour	10^3 kg/ha	1.41	2.75	1.85	0.66
	%	4	8	3	1
100 Hour	10^3 kg/ha	0.73	0.76	0.63	0.29
	%	2	2	1	1
1000 Hour	10^3 kg/ha	10.10	8.18	16.52	17.70
	%	29	22	29	30
Total	10^3 kg/ha	35.09	36.46	57.56	58.20
	%	100	100	100	100

* Significant difference in means at $\alpha = .10$.
** Significant difference in means at $\alpha = .01$.

MATERIALS AND METHODS

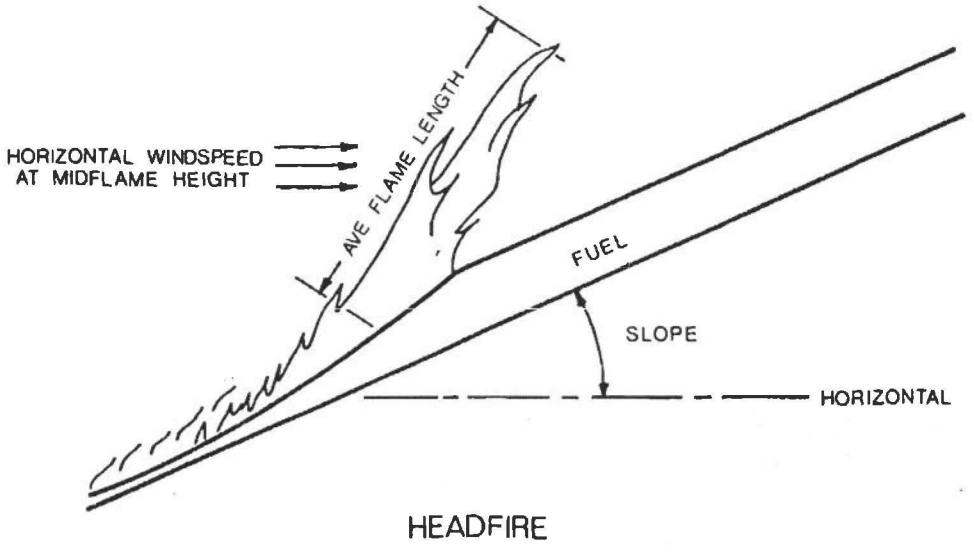
Four locations were divided into 16 (.2-1.0 ha) plots each for a total of 64 plots. The plots were arbitrarily assigned one of four treatments:

1) control (no burn);
2) backfire;
3) single headfire or free-running headfire; and
4) strip headfire.

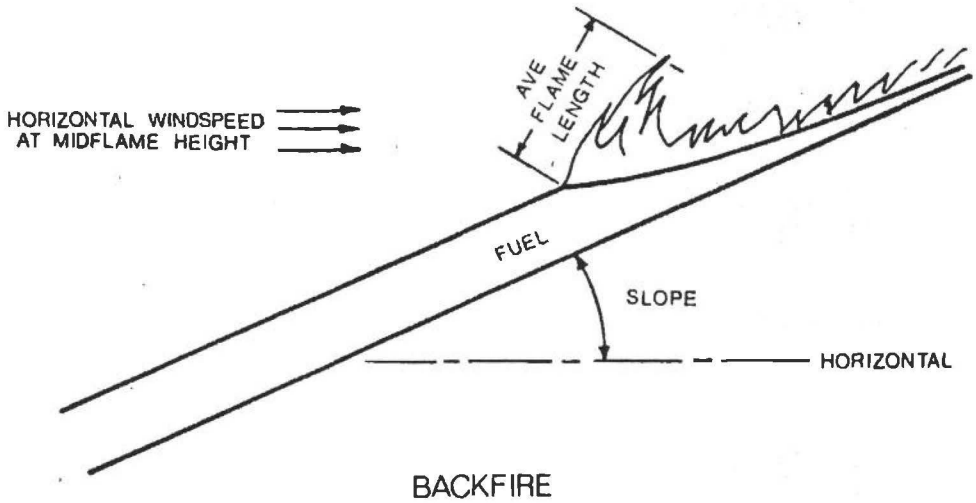
The arbitrary assignment of plots was necessary to insure protection of controls and other no-burn areas in the research area. Plots were delineated by fuel-breaks constructed by D3 and D4 crawler tractors mounted with 8 and 10-ft. blades, respectively. The entire perimeter of the research area was surrounded by a primary fuel break, a low-fuel buffer zone, and a secondary fuel break.

All burning was conducted between the hours of 1:00 and 6:00 pm. Ignition was by hand-held drip torches containing a 75% diesel and a 25% gasoline mixture. Effective wind speed (Albini 1976) and direction was determined for each burn plot at the time of ignition. Backfires were ignited to progress against the effective wind direction. Single headfires were ignited so that a single flaming front moved with the effective wind direction. Strip headfires consisted of several flaming fronts ignited at 2-6 m intervals moving with the effective wind (Figure 2).

Data were collected during three time periods: preburn, burn, and postburn. Preburn data concerned site description variables including fuel loading, fuel moisture, and mensurational descriptors. During the burn, data were collected on fire behavior and weather. Postburn data



HEADFIRE



BACKFIRE

Figure 2. Representations of flaming fronts progressing through unburned fuel in relation to the effective wind (i.e., surface winds and slope gradient).

incorporated changes in the fuel loading and overstory damage due to the treatments.

Fuel loading was determined by two methods, dependent upon the type and size class of fuel. All down woody fuels were sampled using Brown's Planar Intersect Method (1974). These include: 1) 1 h timelag fuel (0-.635 cm. diameter); 2) 10 h timelag fuel (.635-2.54 cm. diameter); 3) 100 h timelag fuel (2.54-7.62 cm diameter); and 4) 1000 h timelag fuel (> 7.62 cm diameter) (Schroeder and Buck 1970, Martin and Brackebusch 1974). A total of 128 Planar Intersect transects were established with two permanent transects per plot. Other fuels, litter, duff, herbaceous grasses, and shrubs were sampled by direct weight collections using 320-0.1 m^2 quadrats (5 quadrats per plot). The 1 h and 10 h timelag fuels were also taken with the quadrats to test for correlation with the Planar Intersect Method.

Fuel moisture at the time of the burn was taken for litter, duff, herbaceous grasses and forbs, 1 h, and 10 h woody fuels. The moisture content of the shrubs was not taken. The quadrat samples were weighed, oven-dried at 70° C for 24 hours, then reweighed. The moisture content of each fuel sample was calculated by dividing the dry fuel weight into the water weight and expressing this number as a decimal fraction.

The burning operations were conducted over 18 separate incon secutive days beginning on September 16, and concluding on October 19, 1978. Three prescribed burns were attempted on any given day: one backfire, one free-running headfire, and one strip headfire. Logistics and weather changes reduced the number of ignitions or changed the type of ignition on seven out of the 18 days. At the time of ignition for

each burn, air temperature and relative humidity were observed using a sling psychrometer at approximately 1.5 m above the ground. Wind speed and direction were estimated with a portable anemometer. During each burn, flame length (Figure 2), rate of fire spread, and residence time, were sampled three times. The rate of fire spread was the distance covered by the flaming front over the period of one minute. Residence time was the duration of time that visible flame existed by random points in the fuel bed.

Mensurational and tree damage data were taken together in the spring of 1979 at the onset of budbreak. Stem dbh was sampled and rounded up to the nearest 5-cm increment. Total height and crown scorch height were measured to the nearest whole meter with a clinometer and 100-m measuring tape. Seedlings less than 0.5 m tall were ignored. Percent crown scorch was estimated to the nearest 10%. Stem density and dbh were obtained by three permanent nested belt transects established in each plot (Figure 3). Stems less than 10 cm were sampled in the 20-m^2 area "A"; 15-cm stems were sampled in the 50-m^2 area "B"; and all stems greater than 15 cm were sampled in the 100-m^2 area "C".

A qualitative assessment was made of the ability of understory fuels to enhance or decrease the crown scorch in the dominant and co-dominant trees. Nine centrally located trees of greater then 15-cm dbh were sampled in each plot. Diameter, height, scorch height, and percent scorch were observed on each tree. All understory fuels including slash, shrubs, and suppressed or intermediate trees within a three-meter radius of the selected tree were tallied.

Another method for measurement of duff reduction was conducted for comparison with the direct weight measurements. Prior to each burn, 16

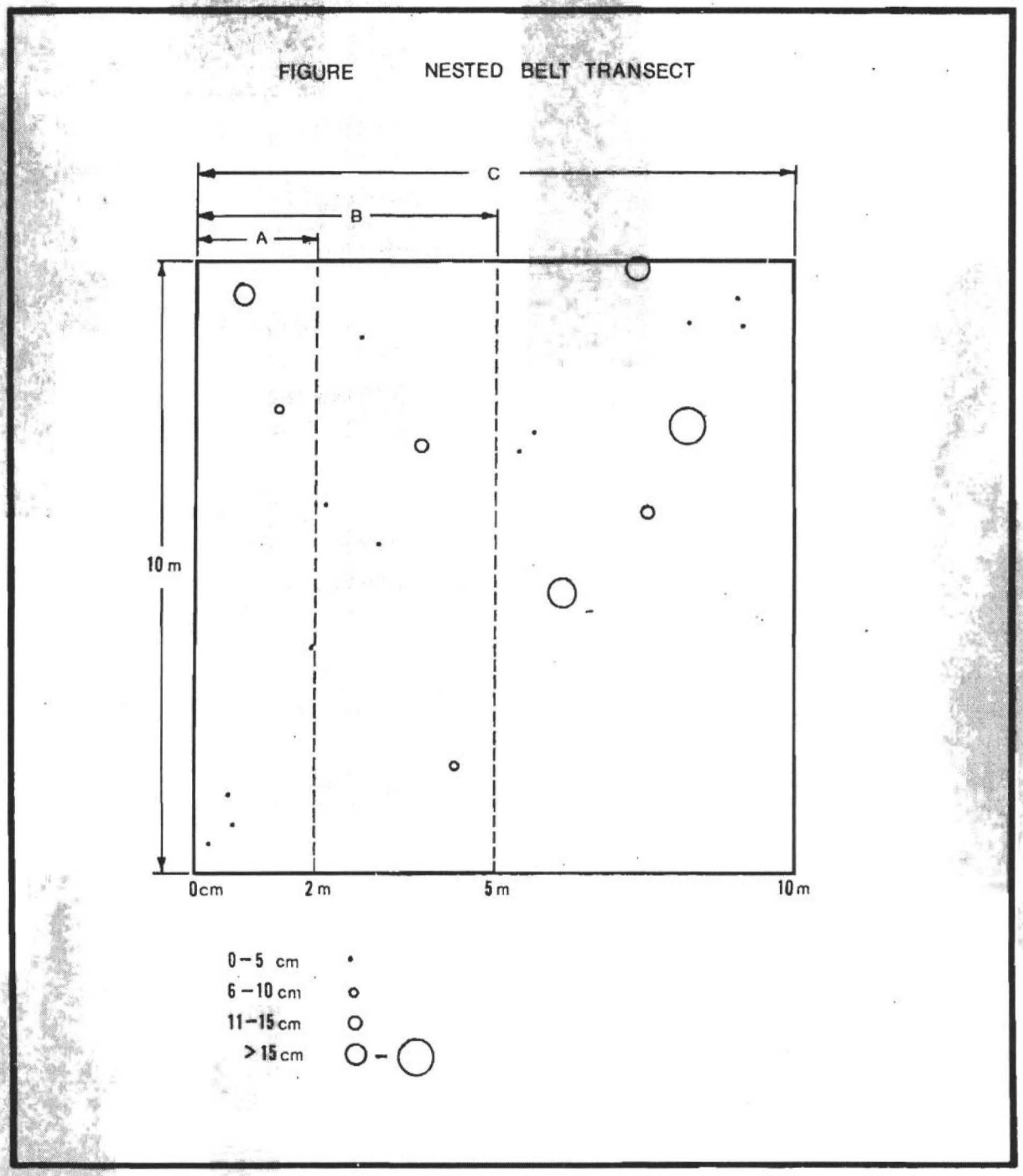


Figure 3. Nested belt transect. Trees less than 10 cm DBH are sampled in area A (20 sq m), trees from 10 and 15 cm DBH are sampled in area B (50 sq m), trees greater than 15 cm DBH are sampled in area C (100 sq m).

bridge spikes (22.9 cm long) were systematically arranged and driven into the ground so that the underside of the spike head was flush with the top of the duff layer. These were examined the following spring (1979). Observations were taken on total duff depth, percent duff consumed, percent of total area burned, and percent of total area disturbed by logging activity.

Actual fuel reduction averages were affected by fuel accumulation between the preburn and postburn fuel loading sampling (fall 1978-summer 1979). This accumulation was estimated for litter, 1 h timelag fuels, and 10 h timelag fuels from 20 .1 m^2 quadrats taken on burned areas during the postburn sampling (Appendix I). Accumulation means were used to adjust the fuel reduction means for the litter, 1 h, and 10 h woody fuels.

Statistical Analysis

A forward stepwise multiple regression procedure was utilized to create quantitative prediction models for fuel reduction, fire behavior, and tree damage variables (SAS 1979). Preburn variables of weather, fuel loading, and fuel moisture were selected as independent variables (Tables 5 and 6). Regressions were run in two parts, all burn treatments combined, and treatments separated by burning method. This procedure was arbitrarily stopped when the addition of a new independent variable failed to increase the coefficient of determination by more than .02. A matrix was calculated to determine correlation between all independent variables. The stepwise procedure was run again for any model that contained highly correlated independent variables ($r > .75$). In each case, the variable first added to the model was retained, while all remaining highly correlated variables were deleted.

Table 5. List of dependent variables used in all burn treatments regression models. The mean, range, and coefficient of variation are given for each variable.

Dependent variable	Definition	Mean	Range	C.V.
	Fuel reduction (individual fuels) (kg/m^2)			
Y_{litter}	Wt loss, freshly fallen litter	0.324	0.0 - 0.927	56.9
Y_{duff}	Wt loss, decomposing duff	1.443	0.0 - 5.346	85.8
$Y_{1\ h}$	Wt loss, 0 - 0.635 cm d woody	0.040	0.0 - 0.396	161.1
$Y_{10\ h}$	Wt loss, 0.635 - 2.54 cm d woody	0.111	0.0 - 1.773	244.9
$Y_{100\ h}$	Wt loss, 2.54 - 7.62 cm d woody	0.025	0.0 - 0.162	163.1
$Y_{1000\ h}$	Wt loss, > 7.62 cm d woody	0.306	0.0 - 3.804	205.6
	Fuel reduction (combined fuels) (kg/m^2)			
$Y_{litter\text{-}duff}$	Wt loss of litter plus duff	1.767	0.0 - 3.835	72.4
$Y_{total\ woody}$	Wt loss of all woody fuels	0.482	0.0 - 5.804	144.1
$Y_{total\ fuel}$	Wt loss of all individual fuels	2.250	0.0 - 6.333	69.4
	Fire behavior			
Y_{spread}	Rate of fire spread (m/s)	1.40	0.13 - 7.52	92.6
Y_{flame}	Flame length (m)	0.67	0.08 - 1.73	59.4
$Y_{residence}$	Residence time of visible flame (s)	30.0	0.0 - 99.0	54.3
Y_{scorch}	Crown scorch height (m)	7.81	1.00 - 27.0	72.6

Table 6. List of independent variables used in regression models (all burn treatments). Mean, range, and coefficient of variation are given for each variable.

Independent Variable	Definition	Mean	Range	C.V.
Fuel (kg/m^2)				
X_{litter}	Preburn litter fuel weight	0.370	0.129 - 0.927	41.8
X_{duff}	Preburn duff fuel weight	2.669	0.650 - 6.171	50.9
$X_{1\ h}$	Preburn weight of 0 - .635 cm d woody fuel	0.0578	0.0015 - 0.396	108.0
$X_{10\ h}$	Preburn weight of .635 - 2.54 cm d woody fuel	0.173	0.0 - 1.906	166.9
$X_{100\ h}$	Preburn weight of 2.54 - 7.62 cm d woody fuel	0.0581	0.0 - 0.294	109.4
$X_{1000\ h}$	Preburn weight of > 7.62 cm d woody fuel	1.242	0.0 - 8.393	125.8
X_{shrub}	Preburn weight of live woody shrubs	0.0468	0.0012 - 0.217	94.5
X_{herb}	Preburn weight of grasses and forbs rooted	0.0453	0.0097 - 0.132	53.6
Fuel Moisture (decimal fraction)				
$X_{MC\text{-}litter}$	1/litter fuel moisture content	1/.136	1/.085 - 1/.222	26.9
$X_{MC\text{-}duff}$	1/duff fuel moisture content	1/.210	1/.087 - 1/.462	50.7
$X_{MC\text{-}1\ h}$	1/1 h woody fuel moisture content	1/.115	1/.084 - 1/.212	22.9
$X_{MC\text{-}10\ h}$	1/10 h woody fuel moisture content	1/.134	1/.087 - 1/.242	26.8
$X_{MC\text{-}herb}$	1/herbaceous fuel moisture content	1/.682	1/.360 - 1/1.130	37.1
Fuel Weight X Moisture Content				
$X_{litter\ fuel}$	$X_{litter} * X_{MC\text{-}litter}$	2.770	0.886 - 7.235	53.3
$X_{duff\ fuel}$	$X_{duff} * X_{MC\text{-}duff}$	11.758	2.139 - 29.609	53.8
$X_{1\ h\ fuel}$	$X_{1h} * X_{MC\text{-}1\ h}$	0.528	0.0143 - 3.494	112.1
$X_{10\ h\ fuel}$	$X_{10\ h} * X_{MC\text{-}10\ h}$	1.284	0.0 - 11.901	149.4
$X_{herb\ fuel}$	$X_{herb} * X_{MC\text{-}herb}$	0.0660	0.0117 - 0.197	62.9
Weather				
X_{wind}	Effective wind speed (km/h)	3.05	0.0 - 6.44	59.8
X_{temp}	Air temperature (°C)	17.8	10.0 - 29.4	21.1
X_{RH}	1/relative humidity of air mass (decimal fraction)	1/.38	1/.24 - 1/.57	21.1
$X_{air\text{-}fac}$	$X_{temp} * X_{RH}$	48.05	17.54 - 115.74	36.8

An analysis of covariance with a protected Least Significant Difference was applied to all dependent variables to test for differences among locations, burn type, location-burn type interaction, and the covariant (preburn duff weight/divided by the duff moisture content). Values were generated for missing observations during the procedure. Analysis of variance with a Duncan's Mean Test was used to test for differences in the preburn independent variables. A qualitative model was developed to determine the effect of understory fuels on the crown scorch height and the effect of fuel bed disturbances on the completeness of the burn.

RESULTS AND DISCUSSION

Forty-eight burns were apportioned among the four locations as follows: Plummer, 12; Worley, 13; Tensed 1, 9; and Tensed, 2, 14. Each location contained four controls (Table 7). A total of 64 treatments were distributed as follows: 15 backfires, 17 single headfires, 16 strip headfires, and 16 controls.

Table 7. Treatment assignment for the four research areas.

Location	Backfires	Single Headfires	Strip Headfires	Controls	Total
Plummer	4	4	4	4	16
Worley	5	4	4	4	17
Tensed 1	2	4	3	4	13
Tensed 2	4	5	5	4	18
TOTAL	15	17	16	16	64

Analysis of covariance was used to test for significance among locations, treatments, and the location-treatment interactions for each

of the dependent variables of fuel reduction and fire behavior (Appendices C and D). A protected Least Significant Difference was then used to consider differences among means.

Several variables were examined as possible covariates for the analysis of covariance:

1) preburn weight of each fuel;

2) weighted average moisture content of litter, duff, 1 h and 10 h fuels; and

3) duff fuel component (preburn duff weight divided by duff moisture content).

The latter was selected for several reasons. First, duff was the dominant fuel on all locations, comprising between 50 and 59% of the total fuel loading of each area (Table 4). Second, duff was the only dead fuel found to be significantly different among locations ($p < .01$). Third, a single covariate for all dependent variables was simple and comparative. Lastly, moisture content of fuels was an important consideration, in that the burning was conducted over a period of 33 days with no intermittent precipitation. Moisture content of duff was thought to be the one fuel category most responsive to long-term fuel moisture trends without displaying the significant diurnal moisture fluctuations that were characteristic of fine surface fuels. Appendix A shows the trend in duff fuel moisture over the period of burning from September 16 to October 19, 1978. Norum (1975) concluded that duff moisture content was a valuable indicator of general fire conditions. He indicated that it integrated weather conditions over a period of time.

Duff fuel component was a significant covariate at the $p < .01$ level for total fuel reduction, duff reduction, and residence time

(Appendices C and D). It was significant at $p < .05$ for the 1 h fuel reduction. Finally, the covariate was significant at $p < .10$ for rate of fire spread. Duff fuel component was not significant for litter, 10 h, 100 h, and 1000 h fuel reduction, nor was it significant for flame length or crown scorch height. All locations means, treatment means, and location-treatment means were corrected for by the covariate. the mathematical relationship for the significant covariates were as follows:

Duff reduction (kg/m^2) = .0696 * covariate
One-hour reduction (kg/m^2) = .00154 * covariate
Total fuel reduction (kg/m^2) = .0754 * covariate
Rate of spread (m/min) = .0379 * covariate
Residence time (s) = .592 * covariate

The location-treatment interaction was not significant ($p < .10$) for any of the fuel reduction or fire behavior dependent variables (Appendices C and D).

Fuel Reduction

Combustion of woody fuels was a surface occurrence. At the surface of the wood, gasified organic compounds mix with oxygen, and at sufficiently high temperatures, ignite. This heat of pre-ignition was an important concept in the relationship between particle size and ignition, and combustion probability. Small-sized fuels had to have a greater percentage of their volume preheated in order to ignite than the larger fuels (Rothermel 1972). However, the total heat required to preheat the surface of larger fuels was greater due to greater gross volume. While a ¼ inch piece of wood required 50% of its volume preheated, and ½ inch only 22%, this calculated to almost twice the wood volume of the larger piece over the smaller piece. This not only increased the rate of combustion in small fuels, but also completeness of consumption. The percent fuel reduction for the four categories of woody fuels was

inversely related to their size, e.g., 1) 0.0-.635 cm d - 56%; 2) .635-.2.54 cm d - 50%; 3) 2.54-7.62 cm d - 37%; and 4) greater than 7.62 cm d - 25%.

During the course of a fire, various fuels had influence upon the combustion of the other fuels. Norum (1975) concluded that small size woody fuels could burn without assistance from the energy radiated from large fuel combustion. However, the consumption of these small fuels was generally more complete when the large woody fuels contributed heat energy. In general, the large woody fuel (1000 h) required preheating from the combustion of the smaller fuels in order to ignite. This was not always the case. Norum burned a plot immediately following a summer rain when the fine fuels were very moist and would not ignite, whereas the large woody fuels were quite dry and burned almost completely.

When the percent reductions of 1, 10, or 100 h woody fuels were compared individually with the percent 1000 h fuel loss, no patterns could be identified. However, when the woody fuels less than 7.62 cm d (3 in) were combined, and the percent reduction of this composite fuel was compared to the 1000 h fuel loss, a trend could be seen (Figure 5). The graph indicates that large woody fuels contributed energy to the combustion of small woody fuels.

Fuel reduction averages were computed at each research area for all dead down fuels. These included fresh fallen litter, decomposing duff, four size classes of surface woody fuel, and combined total fuel loss. Table 3 shows the results of this analysis.

There was no significant difference among locations for the amount of litter consumed by fires ($p \leq .05$). Litter reduction appeared to be highly dependent upon the preburn litter weight. The ranking of mean

Figure 5.

litter reduction by location was almost synchronous with the ranking of mean preburn litter weight by location (Table 4). Litter fuel reduction and preburn litter weight were highest at the Tensed 1 unit. Both were lowest at the Worley unit. For the intermediate rankings, the positions were exchanged. Litter reduction was second at the Plummer unit, third at the Tensed 2; but preburn litter weight was second at the Tensed 2 unit and third at the Plummer unit.

Mean duff reduction was also dependent upon preburn duff fuel weight. The mean preburn duff weight was highest at Plummer, second at Worley, third at Tensed 2, and lowest at Tensed 1. The mean duff reduction by location also followed this order. Duff reduction was significantly less at the Tensed units than at the Plummer unit ($p \leq .01$) and the Worley unit ($p \leq .05$). Duff reduction was not signi ficantly different between the Tensed units, nor was it significantly different between the Plummer and Worley units. Preburn duff weight also differed similarly and significantly among locations (Table 4).

There was no significant difference among locations for fuel reduction in any of the four size categories of dead surface woody fuels ($p < .05$). Furthermore, fuel reduction for these woody fuels appeared to be less dependent upon preburn fuel weight than the litter and duff fuels. The ranking of preburn fuel weights by location showed little resemblance to the ranking of mean fuel weight consumed for any of the four woody fuel categories (Tables 4 and 8).

There was a significant difference among locations for the reduction of the combined fuel loading. Total fuel loss at Plummer differed from the Tensed units at $p < .01$, but did not differ from the Worley unit (p

Table 8. Fuel reduction at each research area including total average weight loss and breakdown of weight loss by dead fuel category. Fuel reduction given in kg/m^2 and percent of preburn average.

		Fuel reduction by category[1]						
		Total	Litter	Duff	1 h	10 h	100 h	1000 h
Location								
Plummer	kg/m^2	2.455 a[2]	0.257 a	1.718 a	0.0297 a	0.0437 a	0.0085 a	0.398 a
	%	42	74	50	66	66	29	22
Worley	kg/m^2	1.714 ab	0.202 a	1.237 a	0.0250 a	0.0893 a	0.0154 a	0.146 a
	%	30	62	37	42	48	24	9
Tensed 1	kg/m^2	1.232 b	0.274 a	0.618 b	0.0291 a	0.0724 a	0.0269 a	0.211 a
	%	35	68	35	55	51	37	21
Tensed 2	kg/m^2	1.139 b	0.227 a	0.676 b	0.0122 a	0.0485 a	0.0149 a	0.160 a
	%	31	59	35	17	18	20	20
Treatment								
Backfire	kg/m^2	2.415 a[2]	0.290 a	1.568 a	0.0300 a	0.1347 a	0.0064 bc	0.387 a
	%	44	82	50	60	81	15	21
Single headfire	kg/m^2	2.273 a	0.337 a	1.453 a	0.0413 a	0.0745 ab	0.0339 a	0.333a
	%	50	82	55	53	31	44	30
Strip headfire	kg/m^2	1.842 a	0.332 a	1.220 a	0.0245 a	0.0443 bc	0.0253 ab	0.196 a
	%	50	97	54	56	42	49	23
Control (no burn)	kg/m^2	0.0 b	0.0 b	0.0 b	0.0 b	0.0 c	0.0 c	0.0 a
	%	0	0	0	0	0	0	0

[1] Fuel reduction means corrected for by the covariate - Duff Fuel Component.

[2] Means in the same column followed by the same letter are not significantly different at $p \leq .05$.

< .05). There was no significant difference between the Worley unit and both Tensed units. The primary reason for these differences was the duff fuel. The preburn weight of the duff was the only fuel category that significantly differed among locations (Table 4). It also was the only category of fuel that differed significantly in fuel reduction. Since the duff comprised from 50 to 59% of the total fuel loading, a significant difference in the reduction of this fuel tended to obscure any offsetting differences in other fuel categories, thereby affecting total fuel reduction. Plummer and Worley had significantly higher preburn fuel loadings than either of the Tensed units, which was partially responsible for their higher total fuel reduction over the Tensed units.

Percent fuel reduction on the Tensed 2 unit was lower than all other units for every fuel category except the 1000 h fuel because of a high level of distrubance of the soil and fuel bed by recent logging.

Fuel reduction means were computed for each of the four treatments: 1) backfires; 2) free-running headfires; 3) strip headfires; and 4) no-burn controls (Table 8). Fuel reduction was independent of the type of burn. There were no significant differences among burn types at $p < .05$ for fuel reduction in litter, duff, 1 h woody, 1000 h woody, and total fuel. There were significant differneces in the 10 h woody and the 100 h woody fuels. However, these two fuels combined account for only 2 to 10% of the total fuel loading, so did not affect the total fuel reduction appreciably. Fuel reduction of the 10 h woody fuels were significantly higher on the backfires than the strip headfires ($p < .05$), but not the free-running beadfires. The ranking was reversed for the 100 h woody fuel reduction. Backfires reduced this fuel signi-

ficantly less than the single headfires ($p < .05$), but not the strip headfires. Among the headfires, no significant differences could be found for the reduction of either the 10 or 100 h woody fuels.

A high precentage of the freshly fallen litter was removed by burning (X = 87%). This was irrespective of the burn type, location, or the burn-time weather and fuel moisture conditions. Sweeney and Biswell (1961) also obtained a high letter consumption (X = 76%) for four understory backfire burns in California. Within the range of burning conditions for this study (Table 6), the litter fuel was the dominant fuel responsible for the propagation of the flaming front. Sweeney and Biswell (1961) attributed the large litter loss to the exposed, uncompacted nature of this fuel, which allowed sufficient oxygen for complete combustion and rapid response to changing atmospheric moisture content. The moisture content of the litter ranged from 9.7% to 24.1% for Sweeney and Biswell's work. In this study, the range was 8.5 to 22.2%. Among treatments, the strip headfires had the highest percent litter reduction. This was possibly due to the high frequency and close spacing of the ignition lines which lead to a more complete consumption.

Duff reduction averaged 53% for the burn types of this study (Table 8). Sweeney and Biswell (1961) averaged 23% duff reduction, although the duff was more moist (X = 27.6%) than it was for this research (X = 21.0%). Actual duff reduction in kilograms per square meter was highest in the backfires, although the percent reduction was lowest when compared to the headfires. The backfire plots had a higher preburn duff fixed loading than the plots of either type of headfire (no significance).

Hough (1968) found that the type of fire seemed to have little effect on the litter plus duff reduction. Backfires consumed 58% of

this layer, headfires 49%. For comparison, the litter plus duff reduction for this study was as follows: backfires, 77%; free-running, 79%; and strip headfires, 84%.

Hough also found no significant differences between headfires and backfires in the percent total fuel reduction in slash-longleaf pine forests (55 versus 56%, respectively). This was also true for this research with backfires, 44%, and single and strip headfires, 50%.

Fire Behavior

Fire behavior was related to weather, fuel loading, and fuel moisture conditions at the time of the burn. Dependent fire behavior variables measured include crown scorch height of ponderosa pine, residence time of visible flame in the fuel bed, rate of spread of flaming front, and the flame length.

There were few significant differences among locations for fire behavior variables (Appendix B). Both crown scorch height and residence time had no significant differences among the locations ($p < .05$). However, there were some observed differences in location means. Tensed 1 had the highest mean scorch height (5.80 m) and the longest residence time (23.5 s). Worley was second, with 5.61 m and 24.9 s, respectively; Plummer third, with 4.51 m and 20.7 s, respectively; and Tensed 2, last with 3.65 m and 16.6 s, respectively. The order was related to fuel moisture content and the sequence that the locations were burned. The prescribed burning was initiated in mid-September of 1978 following a substantial amount of rain in August. Burning was concentrated in the Plummer and Tensed 2 research units at the beginning of the month-long burning period, while the majority of plots burned at the end of the burning season were in Tensed 1 and Worley research areas. Since no

Table 9. Description of three fire behavior variables for each of three types of prescribed fires. Fire behavior parameters identified by means, range, and coefficient of variation.

Fire parameter	Mean	Range	C.V. (%)
Backfires			
Rate of spread (m/min)	0.234	0.132 - 0.427	34.3
Flame length (m)	0.284	0.132 - 0.610	46.5
Residence time (s)	25.0	0.0 - 54.3	64.5
Single headfires			
Rate of spread (m/min)	1.871	0.792 - 3.048	40.7
Flame length (m)	0.855	0.325 - 1.727	41.3
Residence time (s)	36.3	12.0 - 99.0	55.0
Strip headfires			
Rate of spread (m/min)	1.958	0.549 - 7.518	85.2
Flame length (m)	0.854	0.076 - 1.524	41.9
Residence time (s)	27.8	8.6 - 42.0	33.9

rainfall occurred on the sites during the burning period, the fuels were dried in the weather and burned in the latter part of this study. Graphs A and B of the duff moisture content versus time elapsed shows this trend (Appendix A). The lower scorch heights and the shorter residence times in the Plummer and Tensed units were due to ignition under conditions of higher fuel moisture.

Fire spread rate also had no significant differences among locations ($p < .05$). However, the rate of spread was considerably higher at Plummer than the other three units. Flame length, which had some effect on the spread through the preheating of fuels, was also highest at Plummer. Flame length at Plummer was not significantly greater than that of Tensed 1, but was greater significantly than both Tensed 2 and Worley ($p < .05$). Tensed 1, Tensed 2, and Worley did not differ significantly from each other in flame length ($p < .05$). Flame length and spread rate were propagated by such fine fuels as litter and/or exposed matted duff on the ground, and above ground fuels such as grasses and cured, attached shrub leaves. This was most dramatic in headfires because of the greater preheating of fuels and the tendency to spot firebrands. Plummer had the greatest preburn fuel loading of shrubs and herbaceous fuels of any location, which possibly contributed to the high spread rate and flame length.

Fire behavior variable means were compared among the four treatments (Table 10). There were no significant differences between the two types of headfires for any of the fire behavior variables. Both headfires had higher means than the backfires for all variables. These differences were significant at $p < .05$ for all of the fire behavior variables except residence time. Both headfires were also significantly

Table 10. Fire behavior variable means by treatment including crown scorch height, flame residence time, rate of fire spread, and flame length.

Treatment	Scorch height[1] (m)	Residence time (s)	Rate of fire spread (m/min)	Flame length (m)
Backfire	2.84 b[2]	26.1 a	0.244 b	0.303 b
Single headfire	9.46 a	31.9 a	1.826 a	0.783 a
Strip headfire	7.28 a	29.3 a	1.978 a	0.810 a
Control (no burn)	0.0 b	0.0 b	0.0 b	0.0 c

[1] Means corrected for by the covariate - Duff Fuel Component.
[2] Means in the same column followed by the same letter are not significantly different at $p \leq .05$.

greater than the no-burn controls for all four fire behavior variables. Finally, the variable means for backfires were always greater than the controls. However, these differences were significant only for residence time and flame length.

The preheating of the unburned fuel bed was the one characteristic that best described the differences between headfires and backfires. Wind and slope were the causal factors that moved the flames closer to the unburned fuel bed in a headfire and away from the fuel bed in a backfire (Figure 2). Radiant and convective heat energy from the flames impinged upon the unburned fuels ahead of the front, causing these fuels to increase in temperature and lose moisture. Anderson (1969) concluded that radiant heat transfer accounted for only 40% of the total heat flux necessary to sustain a spreading fire. Convective heat transfer at the interface of the combustion zone and the new fuel probably accounted for the rest. In headfires, the radiant heat transfer and the convective heat transfer acted together in primarily the same direction, thus causing a multiplicative increase in the preheating of the fuel bed. In backfires, however, convective heat transfer acted in the opposite direction as the progression of the front. Since only radiant heat was impinging upon the potential fuel ahead, the preheating of backfires was quite low. This dramatically reduced the fire's intensity and slowed the rate of progress of the flaming front.

Strip headfires had a higher rate of spread and flame length than the free running headfires, but a lower crown scorch height. A single flaming front, with a convective heat column, tended to set up an artificial air circulation pattern that involved an increased speed of the prevailing surface winds. This fact was significant because many close,

ignited flaming fronts tended to influence each other's fire behavior. Thus any new fire that was ignited downwind and/or downslope of the initial front progressed rapidly through the unburned fuels toward the latter front. The convective surface winds generated longer flame lengths and faster rates of spread. Quickly, however, the new front contacted the burned fuels of the previous front, thereby interrupting the accelerating fire. A free-running headfire (e.g., uninterrupted fuel bed) grew to a maximum fire intensity by the local fuel and weather conditions. However, in the case of strip headfires, the actual attained fire intensity was held below the potential maximum simply by reducing the distance between ignition strips. The 3 to 6 m spacing of strips used in this study did prevent the fire intensity from reaching its potential maximum. The scorch height was lower in the strip headfires than the free-running headfires. Average effective wind speeds for both types of headfires were approximately equal (single- 3.3 km/h, strip- 3.4 km/h), so this was not a determining factor in the crown scorch height differences observed.

Residence time showed no significant differences among burn types. In porous fuel beds, the residence time has been shown to be controlled by the fuel particle size, a direct relationship (Anderson 1969). Ignition technique appeared to have little effect.

R & D - REGRESSION MODELS

For prescribed burning to be used successfully in seral ponderosa pine, the variables had to be quantified. A total of 22 independent variables were regressed on 13 different dependent variables of fire behavior and fuel reduction (Table 5). The limitations of the multiple

regression models were the ranges of the independent variables (Table 6). Burning the ponderosa pine stands when preburn conditions of weather, fuel loading, and fuel moisture were not within these ranges might have produced unexpected results of fuel reduction and fire behavior.

Fuel moisture content ranges were as follows: 1) litter, 8.5-22.2%; 2) duff, 8.7-46.2%; 3) 0.635 cm woody (0-¼ in), 8.4-21.2%; 4) .635- 2.54 cm woody (¼-1 in), 8.7-24.2%; and 5) herbaceous, 36.0-113.0%. Percent fuel moisture content was inversely related to fire behavior and fuel reduction (Rothermel 1972). Thus, a transformation was deemed necessary to change this to a direct relationahip. The percent values were changed to a decimal fraction and converted to its reciprocal (Table 6).

Composite fuel variables were formed for the litter, duff, 1 h, 10 h, and herbaceous fuels by dividing the preburn weight of each fuel by its fuel moisture content (Table 6). This was an attempt to measure the amount of energy supplied by each of these fuels to the fire behavior and fuel reduction. The fuel size determined the potential energy stored in the fuel, while the fuel moisture content was a measure of its availability, and both determine its ability to ignite. Stockstad (1975) found that the moisture content in pine needles was directly related to the amount of time for this fuel to ignite at any temperature.

Weather and slope variables were also examined. Ambient air temperature ranged from 10 to 29.4° C. Relative humidity was also inversely related to fire behavior (range = 24 to 57%), and a reciprocal transformation was used indentical to the fuel moisture content variables. A composite weather variable was formed from the product of the temperature and relative humidity reciprocal.

Wind and slope have similar effects on a flaming front due to the degree of radiant and convective heat energy impinging upon the unburned fuel bed. Another composite variable was developed to incorporate both of these factors. It was a vector analysis of the wind speed and direction and the slope gradient and direction (Figure 2). It was estimated from the nomographs in Albini's (1976) research. Effective wind speed for this research was less than or equal to 6.4 km/h (4 mph).

The regression models for this research are formed from a forward stepwise multiple regression procedure. The models for each dependent variable were created in two parts: 1) all burns combined (n = 48), and 2) each burn type, backfires (n = 15), single headfires (n = 17), and strip headfires (n = 16). The stepwise procedure added one independent variable at a time (entry level: $p < .50$) and reevaluated the equation for non-significant variables, deleting any predictor variable that had alpha greater than .20. Pearson's linear correlation matrix, among all of the independent variables, was calculated for the independent variables. Any equation with two or more highly correlated independent variables ($r \geq .75$) was re-run after deleting the latter correlated variable. Final models were subjected to further deletions when there was poor improvement in the coefficient of determination and poor confidence interval for the beta coefficients of the individual variables.

Fuel reduction equations were created for each of six categories of dead surface fuel: 1) fresh fallen litter (unmatted); 2) decomposing duff (matted); 3) 1 h timelag woody fuels (0-.634 cm d); 4) 10 h timelag woody fuels (.635-2.54 cm d); 100 h timelag woody fuels (2.54-7.62 cm d); and 6) 1000 h timelag woody fuels ($\geq$ 7.62 cm d) (Tables 11-16).

Table 11. Regression models for reduction of freshly fallen litter (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95 % confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.0729			
	1	+1.07 (± 0.15)	Litter wt (kg/m^2)	0.0001	0.810
		Summary: $Y_{litter} = -0.0729 + 1.07\ X_1$			
		$R^2 = 0.810$ pF = 0.0001			
Backfires	0	-0.0678			
	1	+0.130 (± 0.055)	Litter: wt/moisture content (kg/m^2)	0.0002	0.659
		Summary: $Y_{litter} = -0.0678 + 0.130\ X_1$			
		$R^2 = 0.659$ pF = 0.0002 $\bar{Y} = 0.262\ kg/m^2$ Range = 0 - 0.575 kg/m^2			
Single headfires	0	-0.0404			
	1	+1.01 (± 0.10)	Litter wt (kg/m^2)	0.0001	0.966
		Summary: $Y_{litter} = -0.0404 + 1.01\ X_1$			
		$R^2 = 0.966$ pF = 0.0001 $\bar{Y} = 0.376\ kg/m^2$ Range - 0.164 - 0.927 kg/m^2			
Strip headfires	0	-0.0115			
	1	+0.987 (± 0.109)	Litter wt (kg/m^2)	0.0001	0.964
		Summary: $Y_{litter} = -0.0115 + 0.987\ X_1$			
		$R^2 = 0.964$ pF = 0.0001 $\bar{Y} = 0.327\ kg/m^2$ Range = 0.129 - 0.607 kg/m^2			

Table 12. Regression models of duff reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95 % confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-1.25			
	1	+0.678 (± 0.154)	Duff wt (kg/m^2)	0.0001	0.656
	2	+1.75 (± 1.39)	Litter wt (kg/m^2)	0.0147	0.682
	3	+5.01 (± 4.85)	Shrub wt (kg/m^2)	0.0435	0.711
		Summary: $Y_{duff} = -1.25 + 0.678\ X_1 + 1.75\ X_2 + 5.01\ X_3$			
		$R^2 = 0.711$ pF = 0.0001			
Backfires	0	-1.85			
	1	+0.302 (± 0.432)	Duff wt (kg/m^2)	0.1620	0.575
	2	+2.92 (± 2.26)	1 h fuel: wt/moisture content (kg/m^2)	0.0182	0.661
	3	+0.521 (± 0.563)	Effective wind speed (km/h)	0.0729	0.750
		Summary: $Y_{duff} = -1.85 + 0.302\ X_1 + 2.92\ X_2 + 0.521\ X_3$			
		$R^2 = 0.750$ pF = 0.0012 $\bar{Y} = 1.63\ kg/m^2$ Range = 0 - 5.35 kg/m^2			
Single headfires	0	-0.805			
	1	+0.892 (± 0.195)	Duff wt (kg/m^2)	0.0001	0.863
		Summary: $Y_{duff} = -0.805 + 0.892\ X_1$			
		$R^2 = 0.863$ pF = 0.0001 $\bar{Y} = 1.55\ kg/m^2$ Range = 0 - 4.20 kg/m^2			
Strip headfires	0	1.64			
	1	+0.673 (± 0.148)	Duff wt (kg/m^2)	0.0001	0.695
	2	-0.211 (± 0.082)	Effective wind speed (km/h)	0.0002	0.806
	3	-5.77 (± 2.67)	100 h fuel wt (kg/m^2)	0.0008	0.881
	4	-0.0579 (± 0.0412)	Temperature (°C)	0.0122	0.935
		Summary: $Y_{duff} = 1.64 + 0.673\ X_1 - 0.211\ X_2 - 5.77\ X_3 - 0.0579\ X_4$			
		$R^2 = 0.935$ pF = 0.0001 $\bar{Y} = 1.16\ kg/m^2$ Range = 0 - 3.06 kg/m^2			

Table 13. Regression models of one hour (0.0 - 0.635 cm d) woody fuel reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.0176			
	1	+1.01 (± 0.09)	1 h fuel wt (kg/m^2)	0.0001	0.916
		Summary: $Y_{1\ hour} = -0.0176 + 1.01\ X_1$			
		$R^2 = 0.916$ pF = 0.0001			
Backfires	0	-0.00504			
	1	+0.949 (± 0.216)	1 h fuel wt (kg/m^2)	0.0001	0.755
	2	+0.00115 (± 0.00064)	temp/rel humid (°C)	0.0028	0.822
	3	-0.00812 (± 0.00566)	1/1 h fuel moisture content	0.0105	0.904
		Summary: $Y_{1\ h} = -0.00504 + 0.949\ X_1 + 0.00115\ X_2 - 0.00812\ X_3$			
		$R^2 = 0.904$ pF = 0.0001			
		$\overline{Y} = 0.030\ kg/m^2$ Range = 0 - 0.137 kg/m^2			
Single headfires	0	-0.0182			
	1	+1.05 (± 0.10)	1 h fuel wt (kg/m^2)	0.0001	0.969
		Summary: $Y_{1\ h} = -0.0182 + 1.05\ X_1$			
		$R^2 = 0.969$ pF = 0.0001			
		$\overline{Y} = 0.063\ kg/m^2$ Range = 0 - 0.396 kg/m^2			
Strip headfires	0	0.00955			
	1	+0.0846 (± .0201)	1 h fuel wt/moisture content (kg/m^2)	0.0001	0.799
	2	-0.0127 (± 0.0109)	1 h fuel wt/moisture content (kg/m^2)	0.0288	0.852
	3	-0.159 (± 0.142)	shrub wt (kg/m^2)	0.0344	0.900
		Summary: $Y_{1\ h} = 0.00955 + 0.0846\ X_1 - 0.0127\ X_2 - 0.159\ X_3$			
		$R^2 = 0.900$ pF = 0.0001			
		$\overline{Y} = 0.026\ kg/m^2$ Range = 0 - 0.096 kg/m^2			

Table 14. Regression models of ten hour (0.635 - 2.54 cm d) woody fuel reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.0462			
	1	+0.910 (± 0.074)	10 h fuel wt (kg/m^2)	0.0001	0.930
		Summary: $Y_{10\,h} = -0.0462 + -.910\ X_1$			
		$R^2 = 0.930$ pF = 0.0001			
Backfires	0	-0.0202			
	1	+0.458 (± 0.106)	10 h fuel: wt/moisture content (kg/m^2)	0.0001	0.849
	2	-1.27 (± 0.58)	shrub wt (kg/m^2)	0.0009	0.884
	3	-0.00964 (± 0.00471)	duff: wt/ moisture content (kg/m^2)	0.0013	0.924
	4	+0.344 (± 0.270)	litter wt (kg/m^2)	0.0213	0.946
		Summary: $Y_{10\,h} = -0.0202 + 0.458\ X_1 - 1.27\ X_2 - 0.00964\ X_3 + 0.344\ X_4$			
		$R^2 = 0.946$ pF = 0.0001 Y = 0.113 kg/m^2 Range = 0 - 0.655 kg/m^2			
Single headfires	0	-0.0512			
	1	+0.943 (± 0.070)	10 h fuel wt (kg/m^2)	0.0001	0.982
		Summary: $Y_{10\,h} = -0.0512 + 0.943\ X_1$			
		$R^2 = 0.982$ pF = 0.0001 Y = 0.178 kg/m^2 Range = 0 - 1.77 kg/m^2			
Strip headfires	0	+0.0134			
	1	+0.0332 (± 0.0497)	10 h fuel wt/ moisture content (kg/m^2)	0.1768	0.126
		Summary: $Y_{10\,h} = 0.0134 + 0.0332\ X_1$			
		$R^2 = 0.126$ pF = 0.1768 Y = 0.106 kg/m^2 Range = 0 - 0.284 kg/m^2			

Table 15. Regression models of 100 hour (2.54 - 7.62 cm d) woody fuel reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.0121			
	1	+0.506 (± .079)	100 h fuel wt (kg/m^2)	0.0001	0.772
	2	+0.00588 (± .00263)	10 h fuel: wt/moisture content (kg/m^2)	0.0001	0.843
		Summary: $Y_{100\,h} = -0.0121 + 0.506\,X_1 + 0.00588\,X_2$			
		$R^2 = 0.843$ pF = 0.0001			
Backfires	0	-0.0156			
	1	+0.243 (± 0.101)	100 h fuel wt (kg/m^2)	0.0004	0.573
	2	+0.203 (± 0.112)	herbaceous: wt/moisture content (kg/m^2)	0.0029	0.691
	3	+0.150 (± 0.095)	shrub wt (kg/m^2)	0.0070	0.795
	4	-0.00415 (± 0.00385)	effective wind speed (km/h)	0.0432	0.867
		Summary: $Y_{100\,h} = -0.0156 + 0.243\,X_1 + 0.203\,X_2 + 0.150\,X_3 - 0.00415\,X_4$			
		$R^2 = 0.867$ pF = 0.0002			
		$\overline{Y} = 0.0068$ kg/m^2 Range = 0 - 0.074 kg/m^2			
Single headfires	0	-0.0131			
	1	+0.566 (± 0.133)	100 h fuel wt (kg/m^2)	0.0001	0.846
	2	+0.00611 (± 0.00305)	10 h fuel: wt/moisture content (kg/m^2)	0.0008	0.933
		Summary: $Y_{100\,h} = -0.0131 + 0.566\,X_1 + 0.00611\,X_2$			
		$R^2 = 0.933$ pF = 0.0001			
		$\overline{Y} = 0.042$ kg/m^2 Range = 0 - 0.162 kg/m^2			
Strip headfires	0	-0.00312			
	1	+0.520 (± 0.101)	100 h fuel wt (kg/m^2)	0.0001	0.896
		Summary: $Y_{100\,h} = -0.00312 + 0.520\,X_1$			
		$R^2 = 0.896$ pF = 0.0001			
		$\overline{Y} = 0.024$ kg/m^2 Range = 0 - 0.162 kg/m^2			

Table 16. Regression models of 1000 hour (> 7.62 cm d) woody fuel reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	0.00358			
	1	+0.329 (± 0.074)	1000 h fuel wt (kg/m^2)	0.0001	0.577
	2	-3.32 (± 2.20)	1 h fuel wt (kg/m^2)	0.0040	0.606
	3	+0.0982 (± 0.0917)	litter: wt/moisture content (kg/m^2)	0.0369	0.633
	4	-2.72 (± 2.84)	herbaceous: wt/moisture content (kg/m^2)	0.0605	0.662
		Summary: $Y_{100\,h} = 0.00358 + 0.329\,X_1 - 3.32\,X_2 + 0.0982\,X_3 - 2.72\,X_4$			
		$R^2 = 0.662$ pF = 0.0001			
Backfires	0	1.16			
	1	+0.402 (± 0.118)	1000 h fuel wt (kg/m^2)	0.0001	0.594
	2	-8.45 (± 5.06)	100 h fuel wt (kg/m^2)	0.0105	0.705
	3	-0.381 (± 0.248)	10 h fuel: wt/moisture content (kg/m^2)	0.0049	0.788
	4	-0.295 (± 0.283)	effective wind speed (km/h)	0.0495	0.859
		Summary: $Y_{1000\,h} = 1.16 + 0.402\,X_1 - 8.45\,X_2 - 0.381\,X_3 - 0.295\,X_4$			
		$R^2 = 0.859$ pF = 0.0003 $\bar{Y} = 0.405\ kg/m^2$ Range = 0 - 3.80 kg/m^2			
Single headfires	0	-0.201			
	1	+0.307 (± 0.165)	1000 h fuel wt (kg/m^2)	0.0016	0.323
	2	-0.346 (± 0.197)	1 h fuel: wt/moisture content (kg/m^2)	0.0025	0.441
	3	+0.132 (± 0.089)	litter: wt/moisture content (kg/m^2)	0.0080	0.681
		Summary: $Y_{1000\,h} = -0.201 + 0.307\,X_1 - 0.346\,X_2 + 0.132\,X_3$			
		$R^2 = 0.681$ pF = 0.0015 $\bar{Y} = 0.310\ kg/m^2$ Range = 0 - 1.24 kg/m^2			
Strip headfires	0	-0.136			
	1	+0.420 (± 0.108)	1000 h fuel wt (kg/m^2)	0.0001	0.743
	2	-0.565 (± 0.344)	1 h fuel: wt/moisture content (kg/m^2)	0.0044	0.832
	3	+0.0214 (± 0.0232)	duff: wt/moisture content (kg/m^2)	0.0729	0.873
		Summary: $Y_{1000\,h} = -0.136 + 0.420\,X_1 - 0.565\,X_2 + 0.0214\,X_3$			
		$R^2 = 0.873$ pF = 0.0001 $\bar{Y} = 0.209\ kg/m^2$ Range = 0 - 1.58 kg/m^2			

Table 17. Regression models for fresh litter plus duff reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-1.01			
	1	+0.709 (± 0.163)	duff wt (kg/m^2)	0.0001	0.613
	2	+2.40 (± 1.43)	litter wt (kg/m^2)	0.0016	0.691
		Summary: $Y_{litter\text{-}duff} = -1.01 + 0.709\ X_1 + 2.40\ X_2$			
		$R^2 = 0.691$ pF = 0.0001			
Backfires	0	-1.66			
	1	+4.23 (± 1.75)	1 h fuel: wt/moisture content (kg/m^2)	0.0002	0.645
	2	+0.703 (± 0.531)	effective wind speed (km/h)	0.0150	0.692
		Summary: $Y_{litter\text{-}duff} = -1.66 + 4.23\ X_1 + 0.703\ X_2$			
		$\underline{R}^2 = 0.692$ pF = 0.0009 $\bar{Y} = 1.89$ kg/m² Range = 0 - 5.80 kg/m²			
Single headfires	0	-0.935			
	1	+0.923 (± 0.188)	duff wt (kg/m^2)	0.0001	0.829
	2	+0.139 (± 0.097)	litter: wt/moisture content (kg/m^2)	0.0087	0.897
		Summary: $Y_{litter\text{-}duff} = -0.935 + 0.923\ X_1 + 0.139\ X_2$			
		$\underline{R}^2 = 0.897$ pF = 0.0001 $\bar{Y} = 1.93$ kg/m² Range = 0.33 - 4.47 kg/m²			
Strip headfires	0	1.57			
	1	+0.735 (± 0.154)	duff wt (kg/m^2)	0.0001	0.693
	2	-0.234 (± 0.085)	effective wind speed (km/h)	0.0001	0.833
	3	-5.22 (± 2.63)	100 h fuel wt (kg/m^2)	0.0014	0.887
	4	-0.0151 (± 0.0102)	temp/rel humid (°C)	0.0091	0.941
		Summary: $Y_{litter\text{-}duff} = 1.57 + 0.735\ X_1 - 0.234\ X_2 - 5.22\ X_3 - 0.0151\ X_4$			
		$\underline{R}^2 = 0.941$ pF = 0.0001 $\bar{Y} = 1.48$ kg/m² Range = 0.13 - 3.66 kg/m²			

Table 18. Regression models of total wood fuels reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.0478			
	1	+0.307 (± 0.082)	1000 h fuel wt (kg/m^2)	0.0001	0.495
	2	+0.592 (± 0.444)	10 h fuel wt (kg/m^2)	0.0003	0.623
		Summary: $Y_{wood} = -0.0478 + -.307\ X_1 + 0.592\ X_2$			
		$R^2 = 0.623$ pF = 0.0001			
Backfires	0	+0.208			
	1	+0.356 (± 0.131)	1000 h fuel wt (kg/m^2)	0.0001	0.614
	2	-6.92 (± 6.10)	100 h fuel wt (kg/m^2)	0.0315	0.742
		Summary: $Y_{wood} = 0.208 + 0.356\ X_1 - 6.92\ X_2$			
		$R^2 = 0.742$ pF = 0.0003			
		$\overline{Y} = 0.56\ kg/m^2$ Range 0 - 3.84			
Single headfires	0	-0.279			
	1	+0.129 (± 0.074)	10 h fuel: wt/moisture content (kg/m^2)	0.0027	0.673
	2	+0.254 (± 0.220)	1000 h fuel wt (kg/m^2)	0.0298	0.748
	3	+0.870 (± 1.067)	litter wt (kg/m^2)	0.1078	0.795
		Summary: $Y_{wood} = -0.279 + 0.129\ X_1 + 0.254\ X_2 + 0.870\ X_3$			
		$R^2 = 0.795$ pF = 0.0001			
		$\overline{Y} = 0.59\ kg/m^2$ Range = 0 - 2.33 kg/m^2			
Strip headfires	0	-0.129			
	1	+0.424 (± 0.112)	1000 h fuel wt (kg/m^2)	0.0001	0.792
	2	-3.51 (± 2.85)	1 h fuel wt (kg/m^2)	0.0220	0.860
	3	+0.0865 (± 0.0869)	litter: wt/moisture content (kg/m^2)	0.0555	0.898
		Summary: $Y_{wood} = -0.129 + 0.424\ X_1 - 3.51\ X_2 + 0.0865\ X_3$			
		$R^2 = 0.898$ pF = 0.0001			
		$\overline{Y} = 0.30\ kg/m^2$ Range = 0.015 - 1.72			

Table 19. Regression models of total fuel reduction (kg/m^2) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-1.41			
	1	+0.639 (± 0.184)	duff wt (kg/m^2)	0.0001	0.487
	2	+4.04 (± 1.59)	litter wt (kg/m^2)	0.0001	0.609
	3	+0.373 (± 0.159)	1000 h fuel wt (kg/m^2)	0.0001	0.741
		Summary: $Y_{total} = -1.41 + 0.639 X_1 + 4.04 X_2 + 0.373 X_3$			
		R^2 - 0.741 pF = .0001			
Backfires	0	-0.970			
	1	+0.552 (± 0.288)	1000 h fuel wt (kg/m^2)	0.0021	0.526
	2	+4.90 (± 1.88)	1 h fuel: wt/moisture content (kg/m^2)	0.0002	0.659
	3	-1.07 (± 0.69)	10 h fuel: wt/moisture content (kg/m^2)	0.0074	0.752
	4	+0.601 (± 0.726)	litter: wt/moisture content (kg/m^2)	0.1058	0.812
		Summary: $Y_{total} = -0.970 + 0.552 X_1 + 4.90 X_2 - 1.07 X_3 + 0.601 X_4$			
		$R^2 = 0.812$ pF = 0.0012			
		Y = 0.44 kg/m^2 Range = 0 - 6.33 kg/m^2			
Single headfires	0	-1.34			
	1	+0.946 (± 0.236)	duff wt (kg/m^2)	0.0001	0.601
	2	+0.317 (± 0.134)	litter: wt/moisture content (kg/m^2)	0.0002	0.854
	3	+4.47 (± 3.83)	100 h fuel wt (kg/m^2)	0.0278	0.901
		Summary: $Y_{total} = -1.34 + 0.946 X_1 + 0.317 X_2 + 4.47 X_3$			
		$R^2 = 0.901$ pF = 0.0001			
		Y = 2.52 kg/m^2 Range = 0.71 - 5.35 kg/m^2			
Strip headfires	0	-0.0811			
	1	+0.613 (± 0.216)	duff wt (kg/m^2)	0.0001	0.676
	2	-0.168 (± 0.105)	effective wind speed (km/h)	0.0067	0.855
	3	+0.460 (± 0.219)	1000 h fuel wt (kg/m^2)	0.0012	0.916
	4	+2.42 (± 1.80)	litter wt (kg/m^2)	0.0169	0.937
	5	-3.46 (± 2.58)	100 h fuel wt (kg/m^2)	0.0170	0.966
		Summary: $Y_{total} = -0.0811 + 0.613 X_1 - 0.168 X_2 + 0.460 X_3 + 2.42 X_4 - 3.46 X_5$			
		$R^2 = 0.966$ pF = 0.0001			
		Y = 1.78 kg/m^2 Range = 0.21 - 5.38 kg/m^2			

Table 20. Regression models of flame length (m) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	+0.276			
	1	+2.69 (± 1.69)	1 h fuel wt (kg/m^2	0.0025	0.188
	2	+0.00494 (± 0.00608)	temp/rel humid (°C)	0.1086	0.234
		Summary: $Y_{flame} = 0.276 + 2.69\ X_1 + 0.00494\ X_2$			
		$R^2 = 0.234$ pF = 0.0028			
Backfires	0	+0.222			
	1	+0.0511 (± 0.0449)	10 h fuel: wt/moisture content (kg/m^2)	0.0296	0.315
		Summary: $Y_{flame} = 0.222 + 0.0511\ X_1$			
		$R^2 = 0.315$ pF = 0.0296			
		$\bar{Y} = 0.284$ m Range = 0.132 - 0.610 m			
Single headfires	0	0.102			
	1	+2.02 (± 1.37)	1 h fuel wt (kg/m^2)	0.0094	0.446
	2	+0.126 (± 0.123)	duff wt (kg/m^2)	0.0513	0.530
	3	+0.00684 (± 0.00629)	temp/rel humid (°C)	0.0409	0.630
	4	-2.95 (± 3.31)	shrub wt (kg/m^2)	0.0844	0.721
		Summary: $Y_{flame} = 0.102 + 2.02\ X_1 + 0.126\ X_2 + 0.00684\ X_3 - 2.95\ X_4$			
		$R^2 = 0.721$ pF = 0.0044			
		$\bar{Y} = 0.855$ m Range = 0.325 - 1.73 m			
Strip headfires	0	-0.997			
	1	+0.0750 (± 0.0351)	temp (°C)	0.0008	0.416
	2	+0.157 (± 0.131)	1000 h fuel wt (kg/m^2)	0.0265	0.589
	3	+1.98 (± 1.81)	10 h fuel wt (kg/m^2)	0.0402	0.668
	4	+2.82 (± 3.96)	herbaceous fuel: wt/moisture content (kg/m^2)	0.1575	0.725
		Summary: $Y_{flame} = -0.997 + 0.0750\ X_1 + 0.157\ X_2 + 1.98\ X_3 + 2.82\ X_4$			
		$R^2 = 0.725$ pF = 0.0041			
		$\bar{Y} = 0.854$ m Range = 0.076 - 1.52 m			

Table 21. Regression models of fire spread rate (m/min) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-0.316			
	1	+0.409 (± 0.278)	litter: wt/moisture content (kg/m^2)	0.0049	0.117
	2	+0.192 (± 0.234)	effective wind speed (km/h)	0.1062	0.170
		Summary: $Y_{spread} = -0.316 + 0.409\ X_1 + 0.192\ X_2$			
		$R^2 = 0.170$ pF = 0.0183			
Backfires	0	0.106			
	1	-1.24 (± 0.61)	100 h fuel wt (kg/m^2)	0.0018	0.328
	2	+1.06 (± 0.69)	herbaceous fuel: wt/ moisture content (kg/m^2)	0.0096	0.520
	3	+0.184 (± 0.138)	10 h fuel wt (kg/m^2)	0.0188	0.691
	4	+0.00155 (± 0.00184)	temp/rel humid (°C)	0.1033	0.774
		Summary: $Y_{spread} = 0.106 - 1.24\ X_1 + 1.06\ X_2 + 0.184\ X_3 + 0.00155\ X_4$			
		$\underline{R}^2 = 0.774$ pF = 0.0056			
		$\bar{Y} = 0.234$ m/min Range = 0.132 - 0.437 m/min			
Single headfires	0	-0.212			
	1	+0.198 (± 0.134)	1/1 h fuel moisture content	0.0089	0.410
	2	-5.45 (± 4.03)	100 h fuel wt (kg/m^2)	0.0132	0.541
	3	+0.0607 (± 0.0461)	duff: wt/moisture content (kg/m^2)	0.0153	0.713
		Summary: $Y_{spread} = -0.212 + 0.198\ X_1 - 5.45\ X_2 + 0.0607\ X_3$			
		$\underline{R}^2 = 0.713$ pF = 0.0008			
		$\bar{Y} = 1.87$ m/min Range = 0.79 - 3.05 m/min			
Strip headfires	0	-1.79			
	1	+1.28 (± 0.63)	1000 h fuel wt (kg/m^2)	0.0019	0.444
	2	+0.601 (± 0.542)	duff wt (kg/m^2)	0.0412	0.536
	3	-22.1 (± 16.0)	1 h fuel wt (kg/m^2)	0.0158	0.646
	4	+0.171 (± 0.129)	temp (°C)	0.0192	0.716
	5	-15.3 (± 13.1)	shrub wt (kg/m^2)	0.0331	0.833
		Summary: $Y_{spread} = -1.79 + 1.28\ X_1 + 0.601\ X_2 - 22.1\ X_3 + 0.171\ X_4 - 15.3\ X_5$			
		$\underline{R}^2 = 0.833$ pF = 0.0026			
		$\bar{Y} = 1.96$ m/min Range = 0.559 - 7.52 m/min			

Models were also developed for combinations of the aforementioned fuels. These include litter plus duff reduction (Table 17), total woody fuel reduction (Table 18), and total fuel reduction (Table 19).

Models were developed for three fire behavior variables: rate of fire spread, flame length, and residence time of visible flame (Tables 20-22). The last set of models was for a fire behavior/effects variable, crown scorch height on ponderosa pine (Table 23).

Fuel Reduction

Litter

Only one independent variable was necessary to explain most of the variation for the reduction model of freshly fallen litter (Table 11). In all of the equations except the backfires model, this variable was the preburn litter weight. Further examination of the combined burns and both headfires models revealed that all of the β coefficients were approximately equal to 1.00. This suggested that the litter was almost totally consumed in all of the research burns regardless of the prevailing burn-time weather and fuel moisture conditions (see Table 6 for preburn conditions). My field observations agreed.

The backfires model for litter reduction also contained only one independent variable--the litter fuel component (preburn litter weight divided by the litter moisture content. The litter moisture content was significant to this discussion. Stockstad (1975) concluded that above a fuel moisture content of 7.7%, the probability of ignition of pine needles decreased as the litter moisture content increased. The flaming front of backfires contributed little preheating energy to the unburned fuels ahead. As a result, fuel moisture content played an important role in the probability of ignition. It also affected availability of

Table 22. Regression models of residence time (s) for backfires, single headfires, strip headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-16.1			
	1	+11.4 (± 5.7)	1 h fuel: wt/moisture content (kg/m^2)	0.0002	0.417
	2	+51.0 (± 24.1)	litter wt (kg/m^2)	0.0001	0.537
	3	+9.45 (± 5.5)	1/herbaceous moisture content	0.0013	0.616
	4	+2.29 (± 1.84)	effective wind speed (km/h)	0.0163	0.666
		Summary: $Y_{\text{residence time}} = -16.1 + 11.4\,X_1 + 51.0\,X_2 + 9.45\,X_3 + 2.29\,X_4$			
		$R^2 = 0.666$ pF = 0.0001			
Backfires	0	-41.5			
	1	+6.60 (± 2.48)	1/1 h fuel moisture content	0.0004	0.400
	2	+177.8 (± 67.9)	shrub wt (kg/m^2)	0.0005	0.580
	3	+74.5 (± 33.5)	litter wt (kg/m^2)	0.0013	0.696
	4	+7.07 (± 3.11)	effective wind speed (km/h	0.0012	0.806
	5	-2.37 (± 1.29)	temp (°C)	0.0040	0.935
		Summary: $Y_{\text{residence time}} = -41.5 + 6.60\,X_1 + 177.8\,X_2 + 74.5\,X_3 + 7.07\,X_4 - 2.37\,X_5$			
		$R^2 = 0.935$ pF = 0.0001 $\bar{Y} = 25.2$ s Range = 0 - 54.0 s			
Single headfires	0	2.99			
	1	+25.4 (± 12.6)	10 h fuel wt (kg/m^2)	0.0009	0.677
	2	+5.97 (± 3.29)	litter: wt/moisture content (kg/m^2)	0.0020	0.804
	3	+2.44 (± 2.58)	effective wind speed (km/h)	0.0670	0.850
		Summary: $Y_{\text{residence time}} = 2.99 + 25.4\,X_1 + 5.97\,X_2 + 2.44\,X_3$			
		$R^2 = 0.850$ pF = 0.0001 $\bar{Y} = 36.3$ s Range = 12.0 - 99.0 s			
Strip headfires	0	1.15			
	1	+3.58 (± 1.70)	1/litter moisture content	0.0005	0.590
		Summary: $Y_{\text{residence time}} = 1.15 + 3.58\,X_1$			
		$R^2 = 0.590$ pF = 0.0005 $\bar{Y} = 27.8$ s Range = 8.7 - 42.0 s			

Table 23. Regression models for crown scorch height on ponderosa pine (m) for backfires, single headfires, strip-headfires, and all burns combined. Breakdown of equations includes each beta coefficient (β_i) and its 95% confidence interval, and each independent variable (X_i) and its level of significance (α) in the final model equation. The coefficient of determination (R^2) represents improvement to the model by addition of each independent variable.

Model	i	β_i (± 95% C.I.)	X_i	α	R^2
All burns combined	0	-10.85			
	1	+3.95 (± 1.55)	litter: wt/moisture content (kg/m^2)	0.0001	0.312
	2	+36.0 (± 21.4)	100 h wt (kg/m^2)	0.0019	0.382
	3	+3.52 (± 2.80)	1/rel humid	0.0162	0.460
	4	-3.90 (± 2.87)	1/herbaceous moisture content	0.0100	0.521
	5	-3.40 (± 3.01)	1 hour fuel: wt/moisture content (kg/m^2)	0.0821	0.568
	6	+0.937 (± 0.978)	effective wind speed (m/min)	0.0614	0.618
		Summary: $Y_{scorch} = -10.85 + 3.95\ X_1 + 36.0\ X_2 + 3.52\ X_3 - 3.90\ X_4 - 3.40\ X_5 + 0.937\ X_6$			
		$R^2 = 0.618$ pF = 0.0001			
Backfires	0	-7.96			
	1	+1.93 (± 0.53)	effective wind speed (m/min)	0.0004	0.768
	2	-0.0656 (± 0.0351)	temp/rel humid (°C)	0.0076	0.891
	3	+1.21 (± 0.27)	1/litter moisture content	0.0001	0.962
		Summary: $Y_{scorch} = -7.96 + 1.93\ X_1 - 0.0656\ X_2 + 1.21\ X_3$			
		$R^2 = 0.962$ pF = 0.0006			
		Y = 3.42 m Range = 1.0 - 6.5 m			
Single headfires	0	-14.80			
	1	+5.37 (± 4.01)	duff wt (kg/m^2)	0.0147	0.487
	2	+1.49 (± 1.26)	1/litter moisture content	0.0265	0.556
		Summary: $Y_{scorch} = -14.80 + 5.37\ X_1 + 1.49\ X_2$			
		$R^2 = 0.556$ pF = 0.0116			
		Y = 9.7 m Range = 1.5 - 27.0 m			
Strip headfires	0	23.21			
	1	+2.13 (± 1.56)	1000 h fuel wt (kg/m^2)	0.0155	0.436
	2	-4.57 (± 3.07)	1/rel humid	0.0100	0.665
	3	-100.1 (± 87.4)	herbaceous wt (kg/m^2)	0.0340	0.802
		Summary: $Y_{scorch} = 23.21 + 2.13\ X_1 - 4.57\ X_2 - 100.1\ X_3$			
		$R^2 = 0.802$ pF = 0.0016			
		Y = 7.8 m Range = 2.0 - 17.5 m			

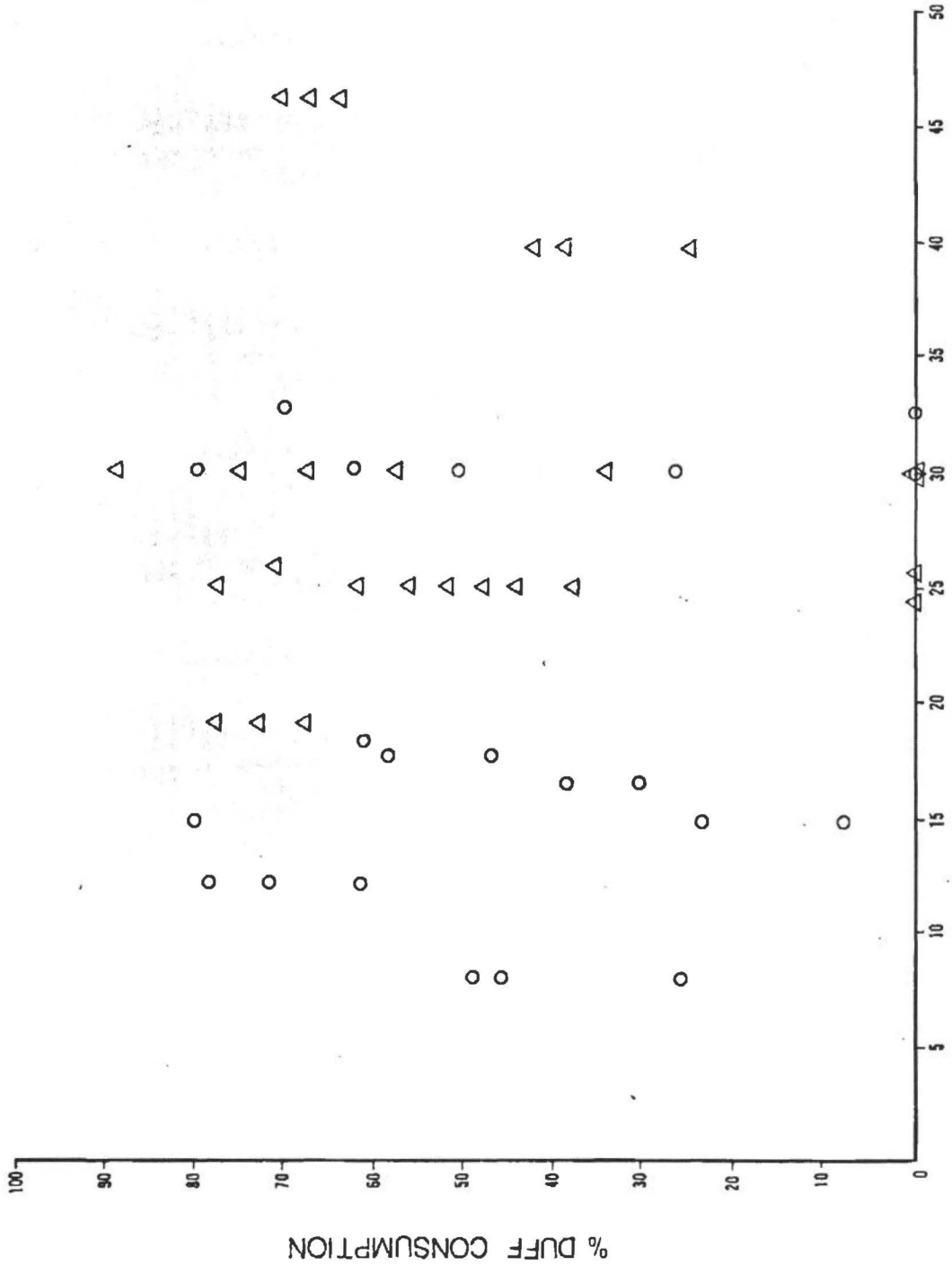
the potential fuel. In headfires, radiant and convective heat energy caused moisture to be expelled from the fine fuels in the fuel bed ahead of the flaming front prior to ignition.

The coefficient of determination for the combined burns model was .810. Segregation of treatments by burn type produced a substantial increase in the R^2 for both headfires (single headfires .966, strip headfires, .964). However, the R^2 for the backfires model was reduced to .659. This may have been due to the higher variation in litter reduction in backfires as illustrated by the coefficient of variations, i.e., strip headfires, of duff reduction. This was probably indirectly associated with the preburn duff weight (first independent variable). For example, rhizomatous shrub species were more prevalent where duff was deeper and undisturbed by recent logging.

When the burns were separated, the coefficient of determination was improved, especially for headfires. The preburn duff weight was the most important independent variable in all three segregated models. In fact, it was the only predictor variable in the single headfires equation under the range of burning conditions used in this study.

Field observation of burning indicated that much duff was consumed in a slow smouldering process that continued long after the flaming front had passed. The likely explanation for the slow combustion was oxygen deficiency or high moisture content of the lower compacted duff or both. The appearance of effective wind speed in both the backfires and strip headfires models confirmed this theory. The wind supplied oxygen to the fire and desiccated the unburned material. However, the beta coefficient of the effective wind speed in the backfires model was positive; in the strip headfires equation it was negative. In a backfire,

Figure 6. Duff reduction (%) in relation to the preburn duff moisture content. Data is segregated by location, Tensed (O) and Plummer - Worley (Δ).



the wind directed most of the convective heat of the flaming front backwards, in relation to the progression of the front (Figure 2), toward the already burning fuels. This aided in the combustion of duff. Hough (1966) found that backfires consumed more litter (fresh and decomposing) than headfires. Most of this difference occurred in the lower decomposing duff layer. In a headfire, the wind or slope or both acted to preheat unburned surface fuels ahead of the front. This increased the flame length and rate of fire spread, but did not necessarily transfer much heat to the lower duff. Rothermel and Anderson (1966) obtained this result in the laboratory using prepared beds of ponderosa pine needles. The vertical depth of the burn in the needles decreased as the speed of the wind increased. The effective wind speed was a highly significant variable in the strip headfires equation (α = .0002), but not in the backfires equation (α = .0729).

At this point, similarity among the regressions ended. The third independent variable in the backfires equation was the 1 h fuel component (0 - .635 cm d woody: weight divided by the fuel moisture content). The positive relationship indicated that fuel acted as a heat source. Its energy contribution to the fire was inversely related to its fuel moisture content. The strip headfires model contained two other predictor variables, both negatively related to duff reductions, 1) the preburn 100 h fuel weight, and 2) the ambient air temperature. The 100 h fuel is relatively large and probably acted as a heat sink.

One Hour Fuel

The 1 h timelag fuel was the smallest category of dead down woody fuel (0 - .635 cm d). The most important independent variable to the prediction of weight loss of this fuel via burning was the preburn

weight of the 1 h fuel (Table 13). It was the only variable in both the combined burns model and the single headfires model, accounting for 92 and 97% of the total variation, respectively.

The backfires model and the strip headfires model were somewhat more complex. Both contained key parameters of the 1 h fuel, the preburn 1 h weight and the 1 h moisture content reciprocal were split into two independent variables, the weight positively related, and the moisture content reciprocal negatively related to 1 h fuel reduction. For the strip headfires model, preburn weight and moisture content were combined into one variable, the 1 h fuel component (preburn weight divided by the fuel moisture content). This was positively related to fuel reduction. Moisture content of 1 h fuels in backfires ranged from 9 to 21% with a mean of 12%. This was similar in the strip headfires, with an 11% mean and a range of 8.5 to 21%. The negative beta coefficient for 1 h fuel moisture content reciprocal could therefore only be explained by the lack of preheating in the backfires. Fuel moisture was apparently too high for easy ignition of the 1 h fuel in backfires. The same fuel moisture did not seem to deter 1 h fuel reduction in the strip headfires with high preheating.

The third independent variable in the backfires equation was the air component (temperature divided by relative humidity). Small 1 h woody fuels responded quickly to changes in the ambient air conditions by absorbing or releasing water vapor and heat energy. Since fuel temperature, especially fuel moisture content, change in a direct relationship to air temperature and relative humidity, respectively, the air component should be directly related to fuel reduction.

The second and third predictor variables in the strip headfires equation were both negatively related to 1 h fuel reduction. Both fuels, 10 h woody fuel and live shrubs, were apparently too moist or too large, or both, to radiate a positive net energy to 1 h fuel, a condition that would have caused more complete combustion of the live shrubs.

Norum (1975) obtained a very similar model for 1 h fuel reduction to the strip headfires model developed in this study. Norum's model included three variables, 1) preburn 1 h fuel weight (positive); 2) 10 h fuel moisture content (positive); and 3) the reciprocal of 1 h fuel moisture content (positive). Norum's first and third independent variables corresponded to 1 h fuel component used here. Norum's second variable, like the equation in this paper, was depicting the 10 h fuel as a heat sink. Fuel reduction of 1 h fuel was directly related to the percent moisture content of 10 h fuel.

The coefficient of determination has not been significantly improved via the segregation of burn type models. The combined burns model required only one independent variable to explain almost 92% of total variation.

Ten Hour Fuel

Ten hour fuel was the second major dead down woody fuel category (.635 - 2.54 cm d). Except for the backfires equation, models for 10 h woody fuel reduction were simple, containing only one independent variable each (Table 14). For example, in the combined burns model, preburn 10 h fuel weight alone explained 93% of total variation of the dependent variable.

The preburn 10 h fuel weight is the only predictor variable in the single headfires model. However, in this model, 98% of the total variation was explained.

The strip headfires equation for 10 h fuel reduction also contained only one independent variable, the 10 h fuel component (preburn weight divided by the fuel moisture content). This model was not statistically significant, however ($p > F = .1768$, $R^2 = .126$), so it is a recommended application of this model under field conditions. Land managers should use either the combined burns model, or better, the single headfires model when they wish to use a headfire ignition technique. Poor regression was in part due to a statistical anomaly. Preburn weight of 10 h fuels was substantially lower in strip headfire plots than either the backfire or single headfire plots ($x = .105$ kg/m^2 versus .166 kg/m^2 and .243 kg/m^2), respectively. Also, 10 h fuel reduction had a very restricted range in the strip headfires, 0 - .164 kg/m^2. The range in backfires was 0 to .655 kg/m^2, whereas the range in single headfires was 0 to 1.77 kg/m^2.

The backfires model contained four independent variables, the most important one being the 10 h fuel component which accounts for 85% of the total variation. The second variable was the preburn shrub weight. This variable was negatively related to 10 h fuel reduction due to its high moisture content and the shading effect of live standing stems. The duff fuel component also had a negative beta coefficient. Duff may have acted as a heat sink to all woody fuels larger than .635 cm d in backfires because of low preheating in this ignition technique. The last independent variable was preburn litter weight. Litter almost totally consumed in all burns. This fine fuel was definitely a heat source that contributed heat energy to all larger fuels, which explains the positive beta coefficient in this model.

Norum's (1975) equation for the reduction of 10 h fuels using strip headfires contained the following four independent variables: 1) preburn weight of 10 h fuels weight (positive); 2) percent moisture content of 10 h fuel (positive); 3) percent moisture content of duff (negative); and 4) the reciprocal of 1 h fuel moisture content (positive). His first two variables corresponded to the 10 h fuel component variable obtained in the strip headfires model of this study. However, the positive β_2 of Norum's equation did not agree with the behavior of the 10 h fuel of this research. This implied that as the moisture content of the 10 h fuel increased, this fuel was more easily consumed. Norum's third and fourth variables appeared to be acting as heat sources in relation to their moisture content. Unfortunately, the poor strip headfires equation obtained in this study prevented any further comparisons.

100 Hour Fuel

Brown (1972) found that woody fuels larger than three centimeters in diameter provided very little heat energy to a propagating flaming front. This demonstrated that large sound woody fuel was not easily ignitable. Many researchers have observed that large woody fuels required an external heat energy source in order to ignite and continue to burn. Frequently, this was provided by the combustion of fine fuels in proximity to larger fuels. The 100 h dead down woody fuel was included in the large fuel category (2.54 - 7.62 cm d).

The four models for 100 h woody fuel reduction had one independent variable in common (Table 15). This was the preburn 100 h fuel weight, only predictor variable in the strip headfires model, accounting for 90% of the total variation.

The combined burns model and the single headfires model contained one other variable, the 10 h fuel component (preburn weight divided by the fuel moisture content). This variable was positively related to 100 h fuel reduction in both models. This smaller fuel acted as a heat source in relation to its moisture content. Obviously, the litter 1 h woody fuel and upper duff were also supplying energy to the larger woody fuels. However, these fuels were either always present (litter and duff) or rare (1 h fuel). Hence, their ability to differentially affect 100 h fuel reduction was limited. The 10 h fuel, however, was a relatively fine fuel that represented 1 to 8% of the total fuel loading (Table 4). Its presence may have significantly affected large woody fuel reduction.

The backfires model departed dramatically from the other three models at this point. The second independent variable, the herbaceous fuel component, was positively related to fuel reduction. In spite of high moisture content, herbs, grasses, and forbs apparently acted as a net heat source. Preburn shrub weight was positively related to 100 h fuel reduction in the backfires model. One possible explanation might have been that shrubs were associated with undisturbed conditions in the fuel bed, an important factor in the propagation of a backfire flaming front. The last independent variable was the negatively related effective wind speed. Increasing wind speeds reduced the preheating of the unburned fuel bed in a backfire. This probably was critical to the amount of combustion in large woody fuels.

The model for 100 h fuel reduction in Norum's (1975) research contained the following four independent variables: 1) preburn 100 h fuel weight (positive); 2) preburn 1000 h fuel weight (negative);

3) percent moisture content of 1 h fuel (negative); and 4) the reciprocal of herbaceous moisture content (positive). As mentioned above, the strip headfires model for 100 h fuel reduction in this study contained one variable, the preburn weight, which equalled Norum's first variable. A second independent variable was entered during the stepwise process, the herbaceous fuel component, but it was removed because of a poor level of significance (α = .1184), and its minor contribution to the coefficient of determination. Although this variable was similar to Norum's fourth variable, the beta coefficient was negative, or opposite of Norum's B_4. Considering the poor level of significance, the herbaceous fuel component might have been positively related to 100 h fuel reduction. This seemed plausible since the herbaceous fuels were drier for this study (x = 68%, range = 36 - 113%) than those of Norum's research (x 187%, range = 92 - 343%).

1000 Hour Fuel

The 1000 h fuels (> 7.62 cm d) were the most prevalent of the woody fuels on sites that were recently logged. For this study, the 1000 h fuel category represented 22 to 30% of the total preburn fuel loading and 66 to 93% of the total preburn woody fuel loading. In spite of the large volume of this material, this fuel class did not usually constitute a high wildlfire risk. The 1000 h fuels were difficult to ignite unless exceptionally dry or in an advanced state of decay (Norum 1975). These fuels were never completely consumed in controlled burning. Fuel reduction in the 1000 h fuel class averaged 9 to 22% in this research. Most of the reduction was limited to rotten logs. The low density of decaying logs caused a greater surface area and a more favorable oxygen:fuel ratio than sound wood (Brown 1974, Martin and Brackebusch 1974).

Brackebusch (1975) reported results of a 19-year, north Idaho study on moisture gain and loss of large sound woody fuels (6, 12, and 18 inch d). From late winter, moisture content of these pieces decreased steadily to a low point sometime during mid- to late August. Brief summer rains had little effect on this trend. After late August, decreasing temperatures and increasing relative humidities act to recharge these large pieces with moisture at rates that were dependent upon piece size and location. Brackebusch's study showed that under full timber cover between mid-September and late October, 6 in d pieces increased from 25 to 32% while the 12 in d pieces changed from 25 to 29%. The same trends existed for these size pieces in exposed locations except the moisture contents were 5 to 6% lower. While these figures were only averages, they gave a rough estimate of the relative availability of fuel of the 1000 h class during the period of burning of this research. Size of this fuel and its relatively high moisture content were the reasons for the low level of consumption in this fuel category.

All regression models for 1000 h fuel reduction (Table 16) contained three or four independent variables. The most important independent variable for all of the models was the preburn weight of the fuel itself.

There were several other consistent trends among these models. Litter and duff material in proximity supplied heat to the 1000 h woody fuel according to the former's fuel availability which is estimated by the litter and duff fuel moisture content (part of the fuel component variable). The litter and duff fuel components appeared in the combined burns and both headfires models and were all positively related to 1000 h fuel reduction.

The small woody fuels (> 7.62 cm d) were negatively related to 1000 h fuel reduction. One hour woody fuel appeared in the combined burns and both headfires models, but 10 h and 100 h fuels occurred only in the backfires model. Norum (1975) stated that large woody fuels usually required heat energy from consumption of smaller fuels in order to ignite and burn. Although he did not specify which fuels, his equations indicated that he included fine woody fuels as heat sources. Models of 1000 h fuel reduction in this study clearly indicated that fine woody fuels were acting as heat sinks. In fact, small woody fuels (Figure 9) were behaving somewhat independently of the large woody fuels in terms of combustion.

Fine herbaceous fuels also acted as a heat sink in the combined burns model, although this variable was not significant at $\alpha = .05$. In this very fine fuel category, fuel moisture was easily driven off. However, herbaceous fuels were not plentiful and were vertically oriented; thus, any net heat release was minor and directed upward away from the surface woody fuels.

The effective wind speed was the last independent variable in the backfires model. Similar to the backfires model for 100 h fuel reduction (Table 15), wind speed was negatively related to 1000 h fuel reduction. Lack of preheating in backfires was again the cause of this relationship.

Norum's (1975) model for the reduction of 1000 h fuels yielded three independent variables, 1) preburn weight of 1 h fuels (positive); 2) preburn weight of rotten 1000 h fuels (positive); and 3) percent moisture content of lower duff (negative). The strip headfires regression model in this study was almost identical except for one

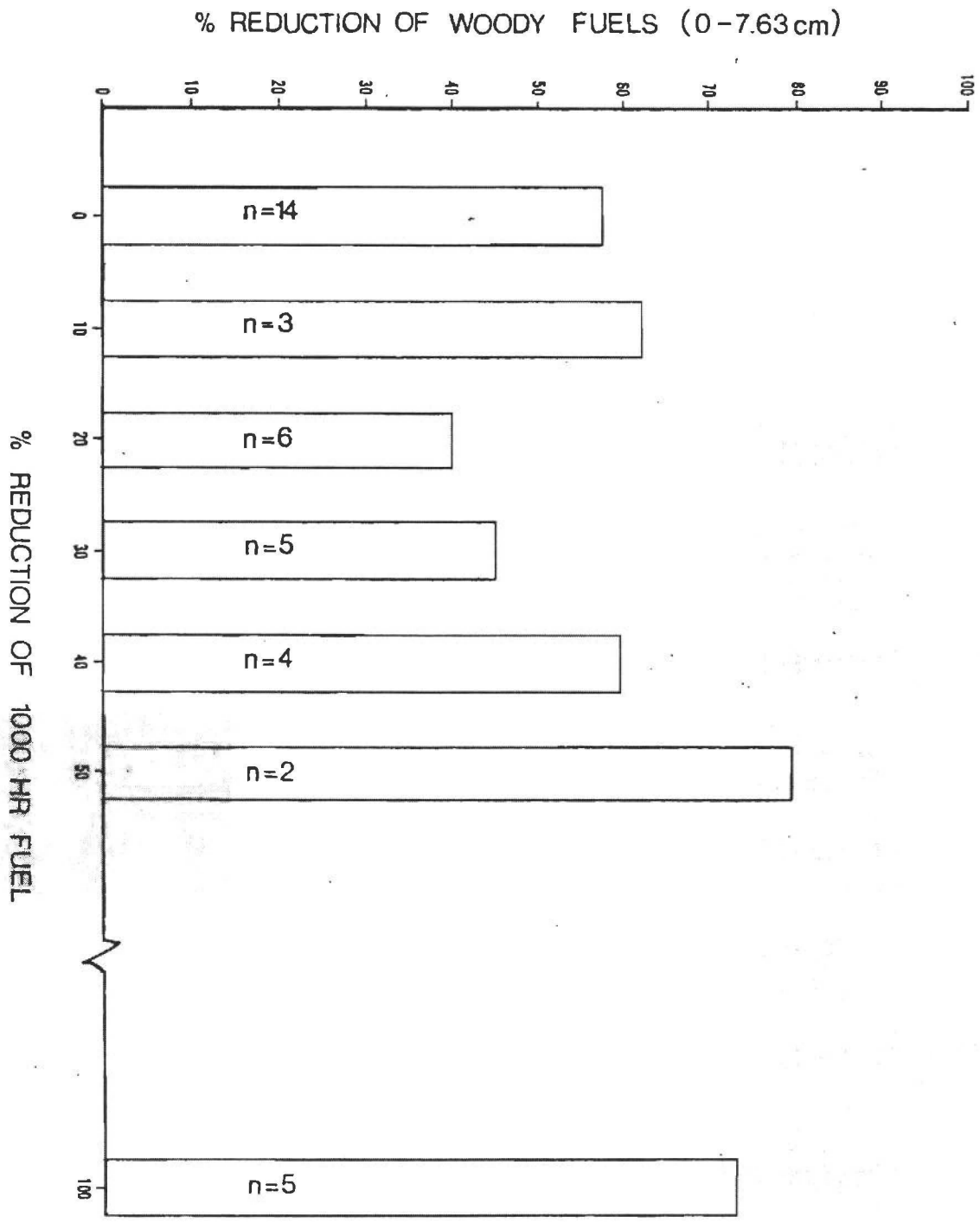
important difference, the 1 h fuel, heat sink or heat source. Moisture content of 1 h fuels was possibly a determining factor. However, the data did not bear this out. One hour moisture content of 16%. In this study, fuel acted as a heat sink, but fuel moisture content averaged 11.5%.

Litter Plus Duff

Certain aspects of forest management have involved the manipulation of both fresh litter and decomposing duff layers. Wildfires have been reduced in frequency, size and damage with controlled burning of the flammable and abundant fresh litter and upper duff material (Martin and Brackebusch 1974). This layer was also a deterrent to natural regeneration of many seral conifer species, including ponderosa pine (Fowells 1965, Schultz and Biswell 1959). Burning of the litter and duff layers has altered the forage quality of forest sites' for wildlife and range management (Garrison and Smith 1974). Finally, these layers intercepted precipitation. Thus, burning has been used to change watershed characteristics (Davis et al. 1968, Zwolinski and Ehrenreich 1967, Zwolinski 1980). A single set of models for predicting the reduction of this composite layer (litter plus duff) would be desirable.

Models for litter plus duff reduction (Table 17) were strikingly similar to those of duff reduction (Table 12). This confirmed the discussions in the litter and duff reduction sections. Litter reduction was, for the most part, independent of environmental conditions within the range of this study.

The combined burns model for litter plus duff reduction contained as independent variables the preburn weights of both fuels. It did not contain the preburn shrub weight as did the duff reduction combined burns regression.


% REDUCTION OF WOODY FUELS (0-7.63 cm)
0
10
20
30
40
50
60
70
80
90
100
% REDUCTION OF 1000 HR FUEL
0
10
20
30
40
50
100
n=14
n=3
n=6
n=5
n=4
n=2
n=5

Backfires regressions for duff reduction and litter plus duff reduction were identical except for the presence of the preburn duff weight in the duff reduction model. However, this third independent variable was not significant in the duff reduction model ($\alpha = .1620$). One-hour fuel acted as a heat source according to available fuel, and effective wind speed supplied oxygen and dehydration to the duff.

The single headfires models were basically the same. The moisture content of litter did appear in the litter plus duff reduction equation, but not in the duff reduction model. This could have been describing the litter fuel availability as a heat source to the underlying duff.

The strip headfires models were very similar also. The first three independent variables were identical, and the last variable differed only in the appearance of the relative humidity in the litter plus duff equation.

In the future, the litter plus duff reduction models will be more meaningful to land managers, and easier to utilize than the two separate equations, litter reduction and duff reduction. Within the range of conditions obtained in this study, managers will be able to assume a virtually complete combustion of the fresh litter, and a less than 100% reduction of duff when using these composite models. In terms of erosion considerations these postburn conditions were desirable even though this might have been optimum for seedbed preparation.

Total Woody Fuel

Woody fuels residues following selective harvesting in the Douglas-fir/ninebark habitat type did not constitute a significant fire hazard because they were very scattered. Woody fuels comprised a minor but consistent percentage of total fuel loading on all research areas,

ranging from 33 to 36% of total fuel loading (Table 4). While not the primary carrier of flaming fronts, accumulated woody fuels could have increased fire intensity, causing damage to the overstory trees. Under hot and dry conditions woody fuels produced large flaming fire brands which contributed to spotting and fire spread. Sound woody fuels were not flammable relative to the litter and upper duff. In fact, they were easily ignitable only when they were in an advanced state of decay and very dry (Martin and Brackebusch 1974). Nevertheless, combustion of these fuels under controlled conditions reduced the overall fire hazard. Reduction of the large woody fuels increased accessibility so had a positive effect on large grazing animals (Garrison and Smith 1974).

There were certain advantages, such as simplicity of use and elimination of a major measurement error, in treating all woody fuel classes as one composite woody fuel. When larger fuel pieces were only partially consumed by a fire, their diameter losses caused postburn sampling in a smaller size class. For example, a 5 cm d piece (100 h size class) might have been reduced to a 1.5 cm d piece (10 h size class). Thus, fuel reduction in the 10-h size class would be confounded by the postburn addition of partially consumed larger fuel. Norum (1975) also encountered this problem. This measurement error was independent of the sampling procedure. A third reason for a composite woody fuel class was the interaction of the various sized woody fuels during fires. While fine woody fuels (i.e., 1 and 10 h) were able to ignite without the assistance of larger woody fuels, consumption of fine fuels was generally more complete when larger fuels burned, radiated heat to small fuels (Norum 1975). Figure 5 is a comparison between the

percent reduction of woody fuels greater than 7.62 cm d (1000 h fuel) with the percent reduction of woody fuels less than 7.62 cm d (1, 10, and 100 h fuels combined). This graph does indicate a trend between the frequency classes 10 and 100% 1000 h fuel reduction (no samples for 60, 70, 80, and 90%). Combustion of the large fuels related to an increase in the smaller woody fuel consumption. Future objectives of many forest land managers may not require precise predictions of individual woody fuel class reductions. A simple knowledge of the above trend in fuel reductions among the size classes may be sufficient.

All four models for total woody fuel reduction contained the preburn weight of the 1000 h fuel as a positively related independent variable (Table 18). This was the predominant preburn woody fuel, averaging between 66 and 93% of the total preburn woody fuel loading (Table 4).

Other similarities were also apparent. The litter fuel appeared to be a heat source for the woody fuels in both headfire equations. Also 10 h woody fuel was present in both the combined burns model and the single headfires model, although in the latter equation, the variable included the 10 h fuel moisture content. In both equations this variable was positively related to fuel reduction. The 10 h fuel was second in importance in terms of preburn woody fuel loading (3-22% total woody fuel loading). Hence, these variables were probably identifying available fuel.

The second independent variable in the backfires equation was the negatively related preburn 100 h fuel weight. This fuel was acting as a heat sink as it did in the 1000 h fuel reduction backfires model (Table 16).

The third independent variable in the strip headfires equation was the preburn 1 h fuel weight. This fuel was apparently acting as a heat sink. Norum (1975) also obtained a model for the reduction of total woody fuel (strip headfires) which contained three variables, 1) preburn 1 h fuel weight (positive); 2) preburn rotten 1000 h fuel weight (positive); and 3) percent moisture content of the lower duff (negative). Note that this equation was almost identical to his model for 1000 h woody fuel reduction, only differing by the beta coefficients. The strip headfires model for total woody fuel reduction of this research departed from Norum's only in the sign of the beta coefficient for preburn 1 h fuel weight. As previously discussed, 1 h fuels in Norum's research probably acted as a heat source to the larger woody fuels, whereas the 1 h fuels were a heat sink in this research.

Total Fuel

The total fuel loading was not a critical measure of wildfire hazard. This quantity simply identified the total potential fuel on the site. If fuel loading was dominated by litter, duff, and 1 h woody fuels, the site was considered very flammable during the dry season with a high probability of ignition and a fast spreading wildfire. If, at the other extreme, the site was primarily loaded with sound 1000 h, 100 h, and duff fuels, the ignition probability and spread rate was much less, but fire control was difficult (Martin and Brackebusch 1974). Fire behavior of a wildfire was dependent on many factors, not the least of which was the available proportion of various sized fuels. For example, the Plummer and Worley research units contained a much greater total fuel loading than either Tensed unit (Table 4). This difference did not indicate the relative need of fuels reduction management, however.

Actually, the Tensed units were very flammable due to the red slash residues remaining on the sites after logging activity. Litter, 1 h, and 10 h fuels were more abundant on the Tensed plots than either of the Plummer or Worley areas. The Plummer and Worley sites had the greatest total fuel loading due to heavier concentrations of duff and 1000 h woody fuels. These areas were logged several years prior to burning.

Total fuel loading may be used as an indicator of the timing of fuel management activities. It is a weak indicator, at best, considering the above discussion. However, a total fuel loading indicator might be improved if comparisons among sites was stratified by habitat type and management activity (i.e., harvesting activity). Land managers may then set up a priority system for fuels management over an entire management area.

The total fuel reduction models were given in Table 19. The reduction of fuel within the dominant preburn fuel categories (Table 4) accounted for the majority of loss in the total fuel loading. Hence, it followed that preburn weights and moisture contents of these fuels were important independent variables in the total fuel reduction regression models. Indeed, the preburn duff weight was the most important predictor variable in the combined burns and both headfires models. The preburn 1000 h woody fuel weight was a positively related independent variable in the combined burns, backfires, and strip headfires models. Finally, the preburn litter weight or moisture content (litter fuel component) or both were present in all four equations and were positively related to total fuel loss.

The equation similarities ceased at this point. As was the case with many of the individual fuel reduction models, the backfires differed

from both headfires for the total fuel reduction models. Fuel moisture content appeared much more frequently in the backfires models than in either headfire equation. In this case, the 1 h woody fuel component and the 10 h woody fuel component were in the backfires model; the former smaller fuel was positively related to fuel loss (heat source) while the latter was negatively related (heat sink). Due to lack of preheating in backfires, fuel size and moisture content determined the amount of available energy.

The preburn 100 h fuel weight was present in both headfires equations. In the single headfires model this independent variable was positively related to total fuel reduction, but in the strip headfires regression it was negatively related. No explanation was found for this difference. Both ignition techniques were headfires and there was no significant difference in 100 h fuel reduction between the two burning types (Table 8). I believe that the negative relationship was more likely (i.e., strip headfires equation). The addition of this variable into the strip headfires equation improved the overall F value from 41.2 to 56.1. The addition of the 100 h preburn weight into the single headfires equation reduced the overall regression F value from 40.8 to 38.2, not enough to remove the variable, but enough to give reason to doubt its value.

The only independent variable not yet mentioned was the effective wind speed in the strip headfires regression, which was negatively related to total fuel reduction. This negatively related variable also appeared in the strip headfires model for duff reduction. From the conclusions of Rothermel and Anderson (1966) it is as reasonable to assume that wind speed was indirectly related to the depth of burning in

duff for headfires. Since duff was the dominant preburn fuel category and was the major source of total fuel reduction, the effective wind speed was an important factor to total fuel loss prediction.

FIRE BEHAVIOR

Flame Length

Flame length was related to the rate at which pyrolyzed gasses were released from burning fuels. Fuels must be quickly ignitable in order to contribute energy to a propagating flaming front, a factor related to the rate of fuel temperature increase. The fine fuel components, particles less than 2.54 cm (1 in) in diameter, were the essential fuels that supplied energy to a propagating flaming front in slash (Brown 1972). Moisture in the fuel had to be vaporized before any appreciable fuel temperature increase could occur, and this required energy.

Prediction of flame length, therefore, was caused in part by fine fuels depending upon fuel moistures. This is precisely what occurred (Table 20). The preburn 1 h woody fuel weight was positively related to flame length in the combined burns and single headfires models, the most important variable in each case. The 10 h fuel component (preburn weight divided by moisture content) was the only independent variable in the backfires equation and accounted for 32% of the total variability. The preburn 10 h fuel weight appeared in the strip headfires model (positive). The herbaceous fuel component appeared in the strip headfires model positively related to flame length, and the preburn shrub weight was present in the single headfires equation, negatively related. Both were relatively fine fuels, vertically oriented, with high moisture contents. If these fuels were sufficiently dry they perpetuated a flame due to their orientation. Note that both the shrubs and herbaceous

fuels were not significant independent variables in their respective equations (α = .08 and .16, respectively). The high variability in fuel moisture contents of these fuels was apparently causing differential responses in flame length of headfires. Finally, the preburn duff weight was in the single headfires equation (positive). The fine fuel particles in the surface duff layer contributed energy to a flaming front. It should be noted that the fresh litter, the most ignitable fuel, did not appear in any of the regressions. This fuel may have provided the energy for an average flame length since most of it was consumed in all fires, and because of its relatively uniform coverage in the fuel bed. The other fine fuels probably appeared in the equations because they enhanced or depressed this average in relation to their characteristics and moisture content.

The weather conditions at burn time were important factors in fire behavior. Temperature was the most important independent variable in the strip headfires equation (positive), and the air component (temperature divided by the relative humidity) appeared in both the combined burns and single headfires models (positive). Air temperature was directly related to fuel temperature, whereas relative humidity was directly related to fuel moisture content. Climate and fuel, temperature and moisture were not identical because of the timelag in the fuel response to change in the climatic conditions. Preburn data gathering took time, in this case, between ½ and 1½ hours. During the interim period between the onset of sample collection and the ignition time, the fuels were changing in sequence with the atmosphere. Data gathering occurred around the noon hour; thus, the general trend during the interim period was for warmer drier fuels, especially fine fuels. Air

temperature and relative humidity provided the only means of assessing this change in the fuels even though this was an indirect approach.

The preburn 1000 h woody fuel weight was present in the strip headfires equation (positive). This variable may be an indirect indicator of the presence of fine fuels and how a flaming front will behave in the fuel bed.

The combined burns model for flame length had a poor coefficient of determination (R^2 = .234). This was not surprising since backfires exhibited very different fire behavior from headfires; flame length of headfires was significantly different from that of backfires (Table 10).

Rate of fire spread

A propagating flaming front was a series of ignitions. Radiant energy from the flames impinged upon potential fuel ahead of the front, first dehydrating the fuel surface, then raising the fuel temperature. The potential fuel began pyrolysis and released combustible gasses in relation to its temperature. When the rate of gas release reached a critical level, the flames ignited these gasses and advanced to a new position (Rothermel 1972). Rothermel's model for rate of fire spread in wildland fuels stated in general terms is as follows:

$$ROS = \frac{\text{Propagating flux}}{\text{Effective bulk density} * \text{Heat of preignition}}$$

The propagating flux (including wind and slope parameter effects) is the heat per unit area per unit time. The effective bulk density is the weight of fuel per unit volume of the fuel bed. The heat of preignition is the heat required to bring a unit weight of fuel to ignition.

Rothermel's theoretical model was related to the independent variables found in the rate of fire spread regressions for backfires,

and both headfires (Table 21). The combined burns model will not be discussed in detail. The poor coefficient of determination (R^2 = .170) of the combined burns model demonstrated fundamental differences in fire behavior of backfires versus headfires (i.e., preheating). Like flame length, rate of spread was significantly different between the backfires and the headfires (Table 10). Thus, the combined burns equation was a poor predictor of fire spread rate. The model did, however, point to the importance of fuel moisture in the most flammable fuel, fresh litter.

The heat of preignition in Rothermel's model above, was inversely related to the rate of spread and depended upon two parameters, 1) change in fuel temperature - ambient to ignition; and 2) fuel moisture content. Rate of fuel temperature change was related to particle size. Some researchers have concluded that speed of ignition in a propagating fire was inversely related to size of the fuel particle (Rothermel and Anderson 1966, Martin and Brackebusch 1974, Brown 1972). Effective bulk density, another variable in the denominator of Rothermel's model was directly related to fuel particle size. Small fuels should enhance the rate of spread, and large fuels may deter it. The determining factor is the fuel moisture content. Hough (1968) and Stockstad (1975) found that rate of spread was inversely related to fresh litter moisture content. Very fine herbaceous fuels appeared as a positively related independent variable in the backfires equation. Energy availability from this fuel was dependent upon the moisture content. Preburn live shrub weight was negatively related in the strip headfires equation. The relatively high bulk density combined with the high moisture content of the shrubs may have caused this relationship. The 1 h woody fuel moisture content reciprocal (positive) was the most important variable in the single

headfires model. The 1 h fuel weight appeared in the strip headfires equation, but was negatively related. There was little continuity of this fuel in the strip headfire plots (C.V. = 108%); which probably caused this relationship. The preburn 10 h fuel weight was positively related to spread rate in the backfires model. The 100 h woody fuel was apparently large enough to deter the spread rate. This independent variable was present in both the backfires and single headfires equations (negative). The largest woody fuel, the 1000 h, appeared as a positively related independent variable in the strip headfires equation. There were two possible explanations for the positive relationship, 1) much of the 1000 h fuel class was rotten; or 2) the frequency of ignition in the strip headfires offset the retarding influence of this large fuel. The last fuel to appear in the rate of spread equations was duff. Preburn duff weight in the strip headfires model and the duff fuel component in the single headfires model. Both were positively related to spread rate. Surface duff was a primary carrier of the flaming front in conjunction with the litter. As an independent variable, the duff was a measure of the continuity of the fuel bed, and affected the spread rate by its moisture content. Although the duff layer was composed of compacted fuels of all other categories, decomposition reduced the effective bulk density with time. There were other factors that reduced the heat of preignition of fuels, and therefore increased the rate of spread, i.e., the weather. Air temperature (positive) was present in the strip headfires equation, and the air component (temperature/relative humidity) (positive) appeared in the backfires model. Since many of the same factors that affected flame length (Table 20) also affect spread rate, the weather variables likely

signified identical circumstances. The temperature and/or relative humidity taken at the moment of ignition indirectly measured the changes in fuel temperature and moisture content that had occurred during the short preburn data collecting period.

Of equal importance with variables included in the models were those not included. The litter fuel did not appear except in the combined burns model. The litter did not appear in the flame length equations either, for the same reason. It was an abundant uniform fuel ($\bar{X}$ = .37 kg/m^2, C.V. = 41.8%) that did not differentially affect the rate of spread within the range of burning conditions of this study. The effective wind speed also was not present in any model except the combined burns equation. The effective wind was of major importance in the propagating flux variable of Rothermel's rate of spread model above. Hough's (1968) research indicated the reason for its absence. He found that the rate of spread in backfires was not influenced by ground winds less than 13 kph (8 mph). Effective wind speeds did not exceed 6 kph in this study. This may have been the cause in the headfire models also.

Residence time

Of the four fire behavior variables sampled, residence time was the only one that showed no significant differences among burn types (Table 10). Correspondingly, the combined burns model for residence time was considerably better (R^2 = .666) than those of flame length, rate of spread, and crown scorch height. Anderson (1969) found that residence time was directly related to fuel particle size. Flame behavior apparently had minimal effect on residence time.

Litter fuel appeared as a positively related independent variable in all four residence time models. Preburn litter weight in the

backfires and combined burns models, and the litter moisture content reciprocal in the strip headfires model (the only variable), and both the preburn weight and moisture content (litter fuel component) in the single headfires model (Table 22). Another fine fuel, the live herbaceous plants, appeared in the combined burns model as the moisture content reciprocal (positive). Preburn live shrub weight was present in the backfires equation, also positively related to residence time. The presence of shrubs may have indicated deeper duff layers which provided more available dry fuel. Fine non-living fuels also positively affect residence time. The 1 h fuel component appeared in the combined burns model; the 1 h fuel moisture content reciprocal appeared in the backfires equation; and the preburn 10 h fuel weight was present in the single headfires model. The larger nonliving fuels did not appear in any of the models.

The effective wind speed was a positive independent variable in the combined burns, backfires, and single headfires models. Surface winds supplied oxygen to the combustion process and dehydrated potential fuel, prolonging residence time. Air temperature is the last independent variable in the backfires equation. It is negatively related to residence time. Air temperature affected the relative humidity which in turn affected fuel moisture. All burns were ignited during the hottest part of the day. Headfires were quickly completed. However, backfires required much time to complete due to the low spread rate. During the course of the backfire burns, the temperature usually decreased in the late afternoon. This may have produced conditions incongruent with the ignition time situation.

Crown scorch height

Crown scorch was an important indicator of tree damage. Scorch was browning of live needles, signifying death due to high temperature of sufficient duration to cause cell damage. Death of needles caused a disruption of normal transpiration in trees. The amount of damage was related to the percent of the total live crown killed. However, the percent crown scorch was not a practical dependent variable since it was dependent on both fire intensity and duration, and height of tree crowns. Crown scorch height, a more functional predictor, was a measure of the level of lethal heat energy (temperature * time), and was not dependent on the presence of tree crowns.

According to Van Wagner (1973), the temperature in a convection column at any height above a flaming front was dependent upon, 1) the intensity of the heat source; 2) the ambient air temperature; and 3) the wind speed in the forest stand. The fire intensity was the rate of combustion. Air temperature represented the starting point of foliar temperature increase. As wind speed increased, two factors changed. First, wind tended to deflect the convection column and introduce cool air (i.e., ventilation), thereby reducing the crown scorch height. Conversely, wind also increased the fire intensity, increasing the scorch height. Van Wagner admitted that his data were limited in range, but he postulated that for low wind speeds in headfires column deflection dominated, reducing the scorch height. With higher wind speeds, increased fire intensity more than offsets the deflection and ventilation of the column, increasing the crown scorch height. The opposite was true of backfires. Hough (1968) found that the rate of spread of backfires was not affected by winds of less than 13 kph

(8 mph). Above this velocity the wind disrupted the flaming front, slowing the rate of spread. Effective wind speed was not an independent variable for the backfires rate of spread model in this study (Table 20). Spread rate was directly related to the rate of combustion, hence in wind speeds greater than 13 kph, backfires had lower fire intensity, and more cool air was entrained into the column. Scorch height was reduced. Low wind speeds did not reduce the spread rate of backfires, but it did increase the amount of available fuel beneath the flaming front through dehydration and infusion of oxygen. Rate of combustion increased as did scorch height.

Crown scorch height in ponderosa pine, like flame length and rate of spread, showed significant differences between headfires and backfires (Table 10). Consequently, the combined burns model for crown scorch height (Table 23) was confusing (six independent variables) and had a low coefficient of determination (R^2 = .618). This model had limited utilization and will not be discussed in detail.

The separation of burns by type significantly improved the models. These three models were important and will be explored more fully here. Fire intensity was affected by the available fuel, which was affected by fuel size, continuity, and moisture content. Fresh litter was the most important fuel. It was abundant (X = .37 kg/m^2), continuous (C.V. = 41.8%), and flammable. The time required for ignition of litter was directly related to its moisture content (Stockstad 1975). The litter moisture content reciprocal (positive) appeared in both the backfires and single headfires equations. The litter fuel component (positive) appeared in the combined burns model. Preburn weight of live herbaceous fuel was present in the strip headfires model. It was

negatively related to crown scorch height because of its high moisture content and its vertical orientation which placed it in the path of the heat pulse. The herbaceous moisture content reciprocal was negatively related in the combined burns model. Several other fuels appeared in the models. In the combined burns model, the 1 h woody fuel reduced scorch height, and the 100 h fuel increased it. The preburn duff weight was present in only the single headfires equations (positive). Surface duff had similar properties to the litter in its burning characteristics. This independent variable seemed to represent duff fuel continuity. Preburn duff weight coefficient of variation was 39% for single headfires, 60% for backfires, and 44% for strip headfires. The preburn 1000 h woody fuel weight increased scorch height in strip headfires. This variable may have indirectly signified the abundance of red slash fuels from the logging operations, a very flammable fuel.

The crown scorch height models also contained weather variables. The effective wind speed increased the scorch height in both the backfires and combined burns model. The effective wind speed for this study ranged from 0 to 6.4 kph (0 - 4 mph). The above discussion explained the variable in the backfires equation, but not the combined burns model. Microclimatic effects may have altered the moisture content in the tree canopy via the transpiration rate. High temperature and low relative humidity increased the transpiration rate and increased the atmospheric instability allowing more ventilation of the crown. This water evaporation was a cooling process which reduced the foliar temperature, thus the scorch height. Indeed, the deep rooting characteristic of ponderosa pine allowed for its relatively high transpiration rate, even in hot dry weather (Spomer personal

communication). The air component (temperature divided by relative humidity) reduced the scorch height in backfires, and the relative humidity reciprocal was negatively related in the strip headfires model. The relative humidity reciprocal increased the scorch height in the combined burns model.

Crown scorch height in ponderosa pine appeared to be dependent upon the continuity and moisture content of fuels for heat intensity. It was also dependent on weather, which affected rate of combustion, heat dissipation, and susceptibility of the needles to damage. Steep slope effects on scorch height could not be examined because of the topography which was less than 30%.

Fuel bed Disturbance and Percent Area Burned

The percent of the area disturbed by logging and mechanical piling was not significantly different among locations (Appendix E). Nor was there any difference among the three burn treatments, or the location-treatment interaction.

While the data showed no significant differences, observation and historical evidence (Finan personal communication) identified several differences. First, the logging at Tensed units took place within six months of the prescribed burning, whereas thinning operations at the Plummer and Worley units occurred three years prior to burning. Second, ground machinery differed. Rubber-tired skidders were used at both Tensed areas, whereas crawler tractors were used at the Worley unit. Observation indicated that crawler tractors were also used at the Plummer area, but this could not be confirmed. Third, unmerchantable logging residues were mechanically piled at both the Worley and Plummer area, but not at the Tensed locations. Finally, the season of operation

also differed. Skidding operations were conducted in the summer at the Tensed units, and in winter, on unfrozen ground, in the Worley unit. There was no information on the Plummer unit concerning this fact. The additional machinery activity and the season contributed to more total disturbance of the fuel bed at the Worley and Plummer units. However, these areas had more time to recover than the Tensed units. Recovery of the fuel bed continuity was brought about by the natural accumulation of organic matter by attrition from plants and animals. Severity of disturbance and recovery time were compensating factors that may have contributed to the non-significance of disturbance among locations. Appendix I shows the accumulation of litter, 1 h and 10 h woody fuels between preburn and postburn data gathering. These data did not include all fuels nor were they representative of a full year accumulation, but it did illustrate the point.

The analysis of covariance of the percent area blackened by fire was not affected by location, treatment, or the location-treatment interaction (Appendix F). However, the percentage of area blackened was significantly affected ($p < .02$) by the percent of area disturbed (covariate). Surface duff and fresh litter were primary carriers of the flaming front. Alteration in continuity of this fuel bed affected fire behavior. Numerous passes of heavy machinery exposed mineral soil, thus breaking the continuity of the fuel, and obstructing the propagation of the flaming front. However, complete breaks in the fuel bed were not required to alter the fire's behavior. Anderson (1969) showed that burning rates were related to the fuel bed porosity. Natural litter fuel beds had low porosity. Small changes in this porosity caused large shifts in the burning rate. Hence, even one pass of heavy equipment

over a point would compact the duff and litter, thereby increasing the fuel bulk density, and decreasing the burning rate, rate of fire spread, and flame length.

This analysis demonstrated the need to minimize vehicular activity on managed areas. Cost of prescribed burning can be reduced through this practice because the likelihood of an incomplete burn is reduced. Unburned islands remaining within a "burned" unit may have to be reignited at a later date.

The lack of significance among treatments for the percent area blackened was misleading. The backfire flaming fronts frequently extinguished and had to be reignited during the burning operations. There were two reasons for this quenching of the fire: 1) relatively high fuel moisture, especially during the first half of the burning period; and 2) more importantly, the discontinuity of the fuel bed. Backfires could not preheat fuels that were very far ahead of the fire, nor were they able to generate burning embers that landed ahead of the flaming front (Figure 2). Thus, breaks in the fuel bed constituted a major obstacle to the progression of the backfire front. Without the constant "nursing" of the backfires, the percent area blackened would have been considerably lower than either of the headfires in this study.

Mortality

The mortality data was taken from the Plummer, Worley, and Tensed 1 locations. The thirteen experimental units of Tensed 1 were excluded due to theft of the permanent plot markers. Wind-thrown trees and bark beetle infested trees were tallied as dead, but may not have been killed by fires.

Overall, the no-burn controls had the lowest percent mortality (3.7%) with only 4 stems out of 108 dying during the first post-burn growing season. Backfires were lowest among the burn treatments with 16.6% mortality (27 out of 163 total stems). Strip headfires were slightly higher with 17.4% mortality (20 out of 115 stems). The highest percent mortality occurred in the free-running headfires, 27.9% (46 out of 165 stems). Several researchers concluded that crown scorch was the most likely cause of death by fire (Wagener 1961, Van Wagner 1973). The percent mortality by burn type follows the same pattern as that of crown scorch height (Table 10), controls lowest, followed by backfires, strip headfires, with highest scorch height occurring in single headfires.

The change in basal area, however, described a different picture during the first growing season. The basal area, measured at 4.5 feet above the ground, was reduced by 1.5% in the controls, 2.7% in strip headfires, 4.3% in single headfires, and 5.8% in backfires. Several large, beetle-killed pine in one of the backfires at the Plummer unit caused the high basal area reduction. There was no crown scorch on these trees, thus the fire may not have been a dominant factor in their demise, but cambium damage cannot be ruled out. Basal area growth on the surviving trees was not measured.

Prescribed understory burning did have an immediate effect on the forest stand composition. Figure 7 shows the mortality after one full post-burn growing season. Backfires appeared to be the least harmful to ponderosa pine of any of the four treatments. The seedling category (0-5 cm dbh) gave the best indication of the effects of burning. There was no mortality in the controls, but the mortality in the burns averaged between 47 and 83%. This mortality occurred primarily in hotter burns of all three ignition types.

Figure 7. Percent mortality of ponderosa pine one full growing season postburn. Frequencies categorized by DBH (cm) and ignition technique.

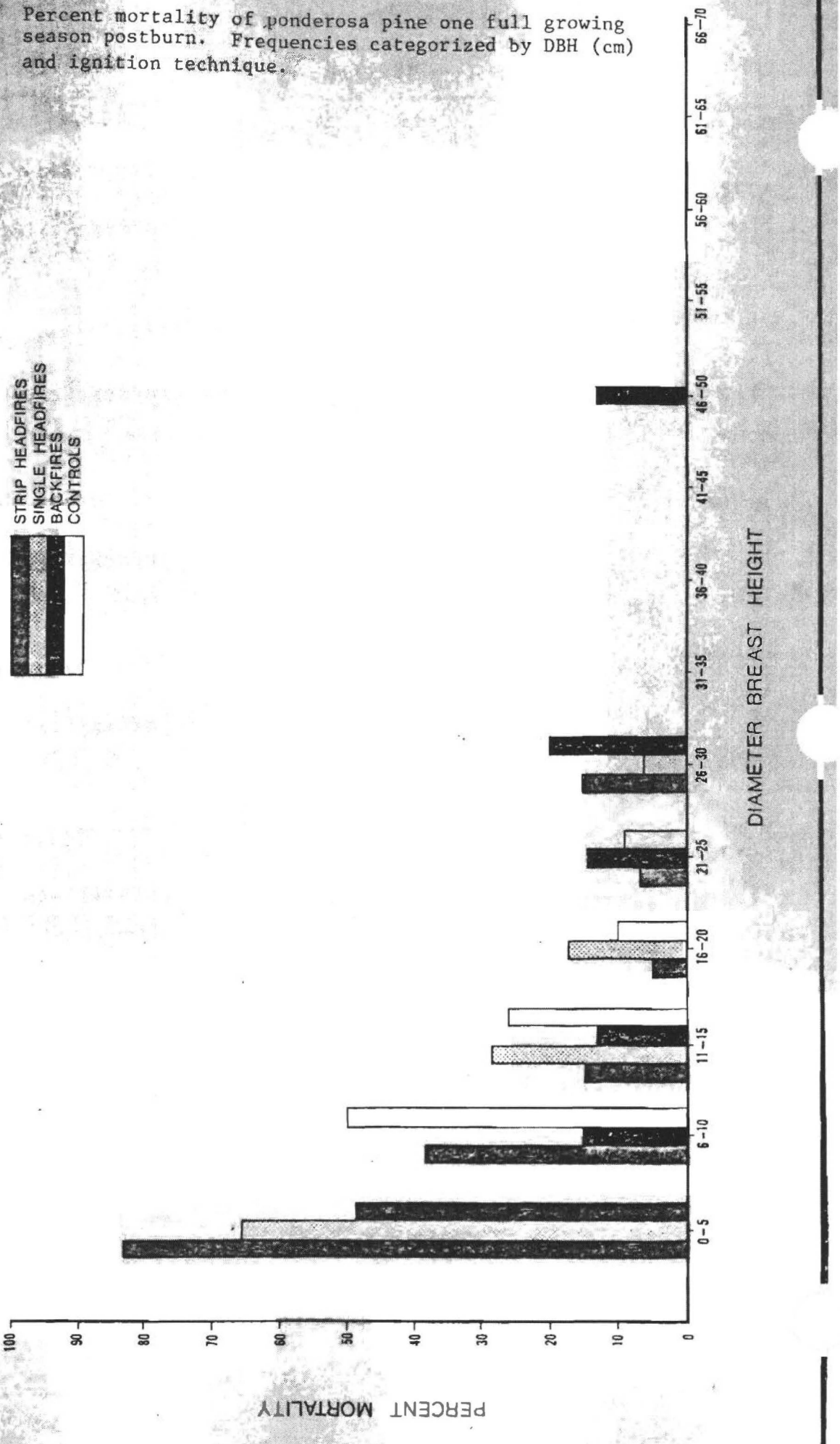


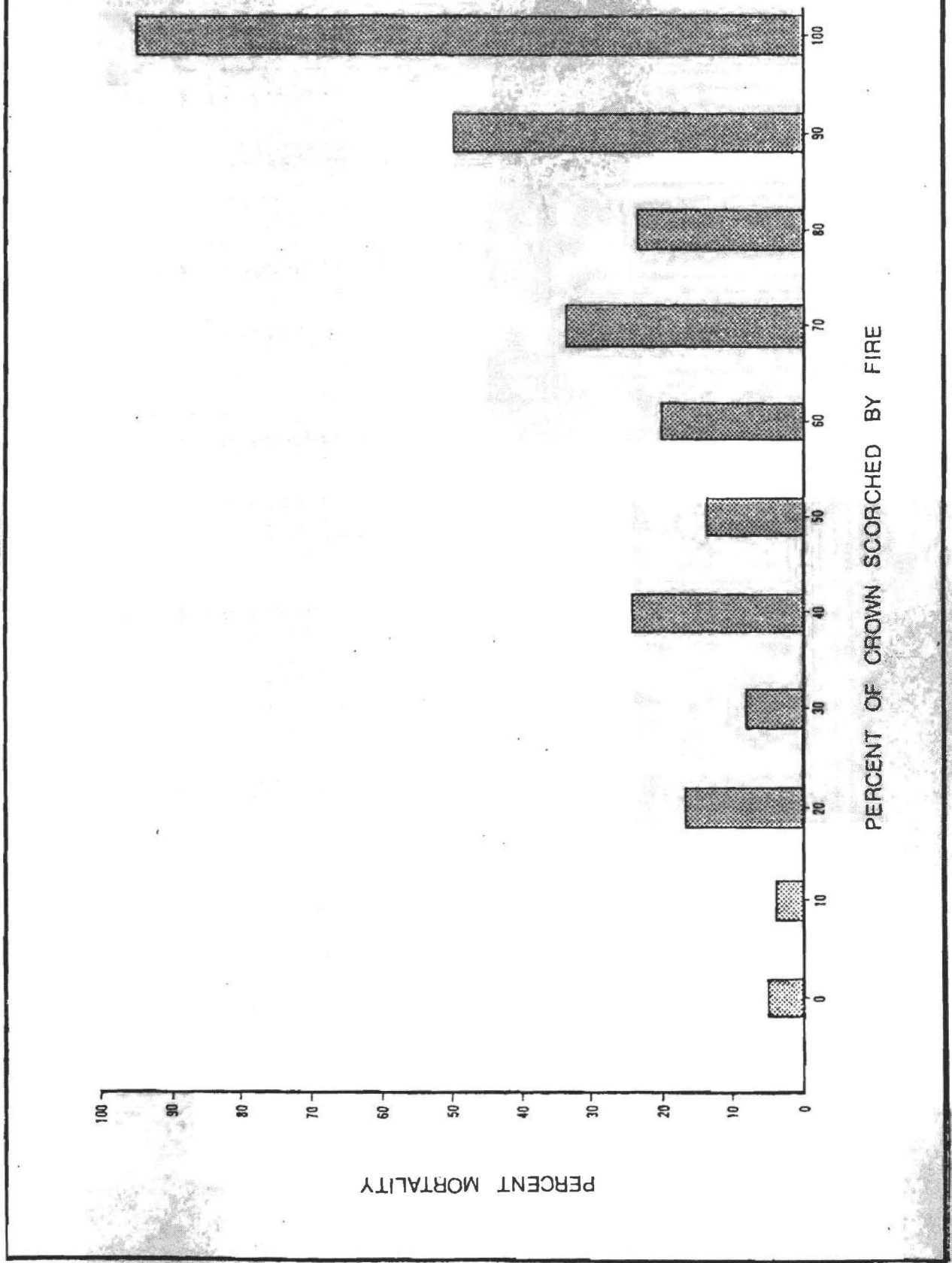
Figure 8 shows that a tree that suffers 100% crown scorch has only a 4.7% chance of survival during the first postburn growing season. Pine that were 90% scorched had a 58.8% chance of survival. The trend for Figure 8 was relatively clear. However, the low sample size in the 40 through 80% scorch classes prevented any precise predictions. Therefore, the minimum management criteria for survival of ponderosa pine after fall fires is less than 90% crown scorch. This agreed with Wagener's (1961) findings in Table 1.

Additional mortality may occur later as an indirect result of burning damage, especially for trees with greater than 50% crown scorch. Insects and disease, or both, may attack or spread as a result of the predisposed condition of the trees. Dieterich (1979) observed 25 ponderosa pine, between 6 and 14 inches dbh, following an Arizona wildfire. The trees had been scorched more than 75%. After two growing seasons, only two trees had died, but after four seasons, six trees were dead (24% mortality).

CONCLUSIONS

One of the more important findings of this study was the lack of significant differences in fuel reduction among the three ignition techniques of backfires, free-running headfires, and strip headfires. This means that land managers can select any of the three methods when prescribed burning without sacrificing the fuel reduction effectiveness. Fire behavior was significantly different between backfires and headfires. Hence, the land managers' decision as to technique should deal with the desired fire behavior in terms of fire control and damage.

Figure 8. Percent mortality of ponderosa pine one full growing season postburn. Percent crown scorch is the ratio of killed needles to total live needles preburn.



This does not mean that the combined burns models for prediction of fuel reduction are the best equations. On the contrary, with few exceptions, the separation of burns by type produced superior predictive models for fuel reduction. The coefficient of determination of the separated models was improved over the combined burns model, or the total variation of the separated models was explained with fewer independent variables, or both of these situations occurred. The factors causing fuel reduction and fire behavior differed depending upon method, particularly between backfires and headfires.

The crux of the difference between headfires and backfires was the amount of preheating of potential fuels. This can best be described with the independent variable, effective wind speed, which was the vector analysis of the effect of ground wind and slope on a flaming front. Backfires progressed against this gradient, and the horizontal convective heat energy was directed towards the already burning fuels. Headfires proceeded with this gradient. The convective energy thus impinged upon unburned fuels ahead of the front. The outcome of preheating on fuel reduction depended upon the position and size of fuel. Headfires tended to consume a greater percentage of woody surface fuels than backfires, especially in the 100 and 1000 h classes. Higher effective wind speed increased 1000 h fuel reduction in headfires, but decreased 100 and 1000 h fuel reduction in backfires. For the subsurface fuel, duff, the opposite was true. Effective wind speed increased duff reduction in backfires, but decreased it in headfires. In terms of fire behavior, the effective wind speed increased residence time in both headfires and backfires but for different reasons. In backfires, more duff was consumed, but in headfires, more litter and

fine woody fuels were consumed. Finally the effective wind speed increased the crown scorch height in backfires.

The weather variables of temperature and relative humidity seemed to exert a modest influence on fuel reduction and a major influence on fire behavior. Hotter, drier conditions favored the consumption of 1 h woody fuels, but had no influence on the larger woody fuels. This was logical since the fine fuels responded quickly to climatic changes. In fact, the temperature and relative humidity measurements, taken at ignition time, represented indirectly, the changes in fuel temperature and moisture content that occurred during the last hour prior to ignition (i.e., preburn fuel sample collection period). Hotter, drier conditions increased the flame length and rate of spread. This was due to the fine fuel temperature and moisture, and the spotting potential increase in headfires. Dry hot conditions also affected tree crowns. Scorch height was actually reduced in ponderosa pine by high temperature/low relative humidities. This may have caused the plants to transpire rapidly cooling the needles, or the unstable atmospheric conditions allows better ventilation of the crowns. Since temperature and relative humidity were interrelated, the composite independent variable, the air component (temperature/relative humidity) was used in this study. Indeed, the air component variable appeared in the separated equations as frequently as the temperature variable and the relative humidity variable combined. I recommend the use of this composite descriptor of the weather conditions over the two presently used variables, air temperature, and percent relative humidity.

Fuels of different sizes and composition were interrelated in terms of fire behavior and combustion. The proximity of fuels on the forest

floor allowed for exchange of heat energy among them. In general, small fuels tended to ignite more quickly than large fuels, and burned more completely. Radiated energy of burning small fuels aided in the ignition and consumption of the larger fuels. Fuel moisture content was another factor. Water vapor had to be driven off by heat before combustion could be sustained. The drier the fuel, the quicker it ignited. When wet, the large woody fuels acted as a heat sink. However, when dry, these burning fuels radiated energy to the smaller fuels, promoting more complete combustion in them (Norum 1975).

Freshly fallen litter was the most important fuel in prescribed understory burning in this habitat type. It was a relatively continuous, abundant, flammable, fuel which acted as a heat source to all other fuels. Preburn weight of litter on its fuel moisture content reciprocal or both were positively related to the reduction of duff, 10 h, 1000 h, litter plus duff, total woody fuel, and total fuel. Litter was highly flammable, which made it a dominant contributor to fire intensity. This fuel appeared in the scorch height and residence time models, and likely accounted for the average flame lengths. Litter probably contributed most of the radiant and convective energy to the rate of spread process.

Surface duff had many of the same characteristics as fresh litter, and in the absence of the latter, was the primary carrier of the flaming front. The preburn duff weight was a measure of the fuel bed continuity. Fuel reduction of all surface woody fuels depended on the ability of the duff to carry the flames between surface fuel particles. Duff moisture content also entered into the availability of duff fuel. Disturbance or high duff moisture content caused an incomplete burn.

Preburn weight of each fuel and its moisture content reciprocal, or both, were the most important independent variables for the fuel reduction models. Simply stated, each fuel must first be present in order to burn, and the fuel's moisture content determined its availability.

The moisture content of various trees was present in the backfires equations more often than in either headfire equations. This situation recurred in both fuel reduction and fire behavior models. Moisture in fuels was much more limiting to ignition in backfires than headfires because of the lack of preheating in the former.

Procedures for prescribed burning

The regression models for fuel reduction provide land managers with the tools to conduct several types of site manipulations via prescribed understory burning. The regression for fire behavior insure a safe, successful burn. A successful burn is one that: 1) accomplishes the objective(s); 2) does not escape the control lines; and 3) does not produce undesirable effects such as crop tree mortality or growth loss. The objectives of a land management activity dictate whether prescribed burning is a viable option, and if it is, which models of fire effects best describe the objective quantitatively. While the models lend a degree of predictability to a highly variable tool, the land manager is still responsible for utilizing the models correctly and effectively.

A successful prescribed burn is dependent upon preburn planning and patience. Once the decision to burn has been made the first step is location and construction of the control line. There are two opposing factors which must be compromised when locating and constructing firelines. First, the fire must be contained within the specific area.

Second, damage to the site due to fireline construction must be minimized. All of the fuel surrounding the burn area could be removed, but this would only satisfy the first criteria. The land manager should look for changes in fuel type and topography, and avoid placing the line near large accumulations of flammable fuels. Ridgetops serve as the best location for firelines, primarily because of the relative lack of fuel and vegetation. Firelines should not be located at the boundary of two fuel types such as a closed canopy forested area bordering an open field.

The following is what I would consider to be the minimum requirements for fireline construction on flat terrain in this habitat type. The entire perimeter of the burn area should be surrounded by fuel breaks of exposed mineral soil. These may be roads or firelines constructed with a crawler tractor equipped with a 12-ft blade. The firelines should be as straight as possible with no turns exceeding 90°. The burns should be pushed to the outside, and leveled at all changes of direction greater than 45°. Vegetation in the path of, or near the line, should be treated as follows: fell all green timber in the path of the fireline, making sure that the stem is cut at ground line, and leaving no protruding stump, fell all green timber whose stems overhang the line, fell all snags within the burn area that are sufficiently tall to fall over the fireline; knock down all brush that either partially or completely overhangs the line; push away and scatter all red slash or old slash piles within 3 m of the fireline on either side and remove all major roots in the mineral soil of the line.

The next step after primary control measures (i.e., fireline) have been established is to wait for the proper conditions of fuel and

weather to occur on the site. In other words, models presented here are only predictions, and are not precise nor accurate unless the preburn conditions are within the ranges of the experiment (Table 6).

The next decision involves the ignition technique. For the land manager, this means which type of burn will be successful at the least cost. In terms of cost, the free-running headfire is the least expensive of the three due to a rapid rate of spread and few ignition sources (i.e., fuel and manpower). Strip headfires are slightly more expensive than single headfires due to higher frequency of ignitions. Backfires are very much more expensive than either headfire due to the low rate of spread. However, a successful burn also depends upon control of adverse effects to the forest stand and site. Thus, great emphasis is placed upon the ability to control fire intensity. This research supports the conclusions of most other studies that backfires offer that greatest amount of control of fire intensity, and are much superior to headfires. Between the headfires, the single headfires offers the least control, essentially none since, by definition, the free-running headfires are allowed to attain maximum intensity for a given set of fuel and weather conditions. With strip headfiring, the land manager is able to reduce the intensity by narrowing the distance between strips. To summarize the decision on ignition technique, for any given potential burning day, the land manager should choose the least expensive method that will not damage the stand.

Fire intensity can be estimated using the crown scorch height models. For example, if one applies the mean values of the independent variables obtained in this research (Table 6) to the scorch height models (Tables 24, 25, and 26) the estimates are as follows:

Table 24. Fire behavior models for free running headfires. Dependent variables are flame length (m), rate of fire spread (m/min), crown scorch height (m), and residence time (s). All independent variables are preburn measurements.

Y	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Flame length	=	0.102	+	2.02 (1 h wt)[1]	+	0.126 (duff wt)	+	0.0068 (temp/r h)[2]	±	2.95 (shrub wt)	0.721
Rate of spread	=	0.142	+	0.170 (1/1 h mc)[3]	+	4.57 (100 h wt)	+	0.0697 (duff fac)[4]	-	0.267 (100 h wt)	0.772
Scorch height	=	-14.8	+	5.37 (duff wt)	+	1.49 (1/litter mc)					0.556
Residence time	=	2.99	+	25.4 (10 h wt)	+	5.97 (litter fac)	+	2.44 (wind)[5]			0.850

[1] wt = weight in kilograms per square meter.
[2] temp = temperature in degrees centigrade.
r h = relative humidity (decimal fraction).
[3] mc = moisture content (decimal fraction).
[4] fac = weight (kg/m^2)/moisture content (decimal fraction).
[5] wind = effective wind speed (vector of slope and wind).

Table 25. Fire behavior models for strip headfires. Dependent variables are flame length (m), rate of fire spread (m/min), crown scorch height (m), and residence time (s). All independent variables are preburn measurements.

Y	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Flame length	=	-0.997	+	0.0750 (temp)[1]	+	0.157 (1000 h wt)[2]	+	1.98 (10 h wt)	+	2.82 (herb fac)[3]	0.725
Rate of spread	=	-1.48	+	1.18 (100 h wt)	+	0.605 (duff wt)	-	18.6 (1 h wt)	+	0.105 (temp)	0.716
Scorch height	=	23.2	+	2.13 (1000 h wt)	-	4.57 (1/r h)[4]	-	100.1 (herb wt)			0.802
Residence time	=	-6.76	+	3.91 (1/litter mc)[5]	+	2.40 (duff wt)					0.653

[1] temp = temperature in degrees centigrade.
[2] wt = weight in kilograms per square meter.
[3] fac = weight (kg/m^2)/moisture content (decimal fraction).
[4] rh = relative humidity (decimal fraction).
[5] mc = moisture content (decimal fraction).

Table 26. Fire behavior models for backfires. Dependent variables are flame length (m), rate of fire spread (m/min), crown scorch height (m), and residence time (s). All independent variables are preburn measurements.

Y	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Flame length	=	0.222	+	0.051 (10 h fac)[1]							0.315
Rate of spread	=	0.106	-	1.24 (100 h wt)[2]	+	1.06 (herb fac)	+	0.184 (10 h wt)	+	0.0016 (temp/rh)[3]	0.744
Scorch height	=	-7.96	+	1.93 (wind)[4]	-	0.0656 (temp/rh)	+	1.21 (1/litter wt)[5]			0.962
Residence time	=	-66.6	+	5.24 (1/1 h mc)	+	111.0 (shrub wt)	+	79.6 (litter wt)	+	4.90 (wind)	0.806

[1] fac = weight (kg/m^2)/moisture content (decimal fraction).
[2] wt = weight in kilograms per square meter.
[3] temp = temperature in degrees Centigrade.
rh = relative humidity (decimal fraction).
[4] wind = effective wind speed (vector of slope and wind).
[5] mc = moisture content (decimal fraction).

1) single headfires scorch height

scorch height = 14.8 + 5.37 (2.7) + 1.49 (1/.136) = 10.7 meters

2) strip headfires scorch height

= 23.2 + 2.13 (1.2) - 4.57 (1/.38) - 100.0 (.045) = 9.2 meters

3) backfires scorch height

= -7.96 + 1.93 (3) - .0656 (48) + 1.21 (1/.156) = 2.7 meters

If the calculated scorch height for single headfires (10.7) is equal to or greater than the mid-crown height on the dominant/crop trees on the site, single headfires should be eliminated as an ignition technique for that particular day. If the calculated crown scorch height for a strip headfire (9.2) is also greater or equal to this critical point, it too should be eliminated as an option or the distance between strips should be reduced. Backfires are the only option left. Within the range of preburn weather and fuel conditions, backfires did not reach this level. In fact, an estimated scorch height of 2.7 meters for the average conditions constitutes very little damage to mature ponderosa pine. The critical level of damage in terms of scorch height might be changed if the land manager is considering using prescribed burning as a thinning agent.

Several factors may be used to narrow the choices of ignition technique. Disturbance plays a major role in fire behavior due to the breakup of the fuel bed. Any disturbance in the fuel bed usually precludes the use of backfires for reasons discussed in the disturbance section of this thesis. Thus, for burning activities proposed in stands that have had no recent harvesting activities, all ignition techniques are possible. However, where crawler tractors or skidders

have been operating in the previous five years, the land manager may be restricted to headfiring techniques. In severely disturbed conditions, the manager may be able to use strip headfires only because of the higher frequency of ignitions.

Another factor important to the ignition technique decision is the weather on the day of the burn, specifically the effective wind speed and direction. Problems in fire behavior arise when the effective wind is light and variable. For example, a ground wind subject to frequent shifts in direction with a speed of 1 to 3 kph on flat terrain will be difficult to control in terms of spotting and fire intensity. This is particularly the case if the manager is attempting a backfire, because changing wind direction will cause a backing front to become a heading flaming front. No wind or a steady wind of greater than 3 kph is desirable. Since the effective wind is a product of both slope and surface winds, the former must also be considered. In terms of fire behavior, slope gradients of more than 25% are usually sufficient to overshadow most surface winds of less than 6 kph.

Understory vegetation, including shrubs and understory trees may also affect damage to the crop trees. In fact, the understory trees appear to have a depressing effect on the scorch height in the crop trees, either by shading or by the interception of the flaming front heat pulses. The relationship was not significant to form any predictable conclusions. However, in stands that have multiple tiers of living vegetation, care should be taken to collect data from the shaded areas beneath crop trees in order to obtain a pertinent sample that reflects the true fuel conditions.

The last step after selection of the ignition technique is the final decision as to whether to burn on the specified day. In other words, will a proposed burn ignited today accomplish the objective(s). For example, given the weather and fuel conditions specified above (mean values for this research), the land manager decides that strip headfiring is the least costly, with acceptable crown scorch. The objective is site preparation for natural regeneration of ponderosa pine (i.e., $\geq$ 75% reduction of the litter-duff layer).

The model for litter plus duff reduction in strip headfires (Table 28) is as follows:

$$\begin{aligned}\text{Litter-duff} = 1.57 &+ .735\ (\text{preburn duff weight}) \\ &- .234\ (\text{effective wind speed}) \\ &- 5.220\ (\text{preburn 100-h weight}) \\ &- .0151\ (\text{temperature/relative humidity})\end{aligned}$$

Given the mean conditions, the model predicts a reduction in the litter-plus-duff of 1.79 kg/m^2. Since the preburn weight of the litter and duff layer is .37 + 2.67 = 3.04 kg/m^2, a strip headfire conducted under the given conditions would result in a 1.79/3.04 = 59% reduction of the litter-duff layer. This does not fulfill the criteria of the objective. Thus, the burn should not be conducted using a strip headfire on this day. A backfire would result in a 93% reduction (2.84/3.04 kg/m^2 if the manager is able to insure a complete burn.

Desirable conditions for burning depend in part on the objective(s). However, for most prescribed burns, fuel reduction, although not a primary factor, is included in the list of objectives. If there is sufficient fuel to carry a fire, the potential may exist for a destructive wildfire (i.e., destructive to the overstory trees). The primary constraint in prescribed understory burning is damage to the overstory trees. Hence, ideal conditions for fall burning are relatively dry fuels combined with cool-moist weather. This serves to

Table 27. Models for reduction of individual and combined fuels (kg/m^2) for free running headfires. All independent variables are preburn measurements.

Y^4	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Individual fuels											
Litter	=	-0.0404	+	1.01 (litter wt)[1]							0.966
Duff	=	-0.805	+	0.892 (duff wt)							0.863
1 hour woody	=	-0.0183	+	1.05 (1 h wt)[2]							0.969
10 hour woody	=	-0.0512	+	0.943 (10 h wt)							0.982
100 hour woody	=	-0.0131	+	0.566 (100 h wt)	+	0.0061 (10 h fac)[3]					0.933
1000 hour woody	=	-0.201	+	0.307 (1000 h wt)	-	-0.346 (1 h fac)	+	0.132 (litter fac)			0.681
Combined fuels											
Litter-duff	=	-0.935	+	0.923 (duff wt)	+	0.139 (litter fac)					0.897
Total woody	=	-0.279	+	0.129 (10 h fac)	+	0.254 (1000 h wt)	+	0.870 (litter wt)			0.795
Total fuel	=	-1.34	+	0.946 (duff wt)	+	0.317 (litter fac)	+	4.47 (100 h wt)			0.901

[1] wt = weight in kilograms/square meter.
[2] h = hour timelag woody fuel.
[3] fac = weight (kg/m^2)/moisture content (decimal fraction).
[4] hour woody refers to the equilibrium moisture content timelag with the atmosphere.
1 hour woody = 0.0 - 0.635 cm d woody piece (0.0 - ¼ in d)
10 hour woody = 0.635 - 2.54 cm d woody piece (¼ - 1 in d)
100 hour woody = 2.54 - 7.62 cm d woody piece (1 - 3 in d)
1000 hour woody = > 7.62 cm d woody piece (> 3 in d)

Table 28. Models for reduction of individual and combined fuels (kg/m^2) for strip headfires. All independent variables are preburn measurements.

Y^6	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Individual fuels											
Litter	=	-0.0115	+	0.987 (litter wt)[1]							0.969
Duff	=	1.64	+	0.673 (duff wt)	-	0.211 (wind)[2]	-	5.77 (100 h wt)	-	0.0579 (temp)[3]	0.935
1 hour woody	=	-0.0002	+	-.0895 (1 h fac)	-	0.0129 (10 h fac)[4]					0.852
10 hour woody	=	0.0134	+	0.0332 (10 h fac)							0.126
100 hour woody	=	-0.0031	+	0.520 (100 h wr)							0.896
1000 hour woody	=	0.0017	+	0.438 (1000 h wt)	-	0.412 (1 h fac)					0.832
Combined fuels											
Litter-duff	=	1.57	+	0.735 (duff wt)	-	0.234 (wind)	-	5.22 (100 h wr)	-	0.0151 (temp/rh)[5]	0.941
Total woody	=	-0.129	+	0.424 (1000 h wt)	-	3.51 (1 h wt)	+	0.0865 (litter fac)			0.898
Total fuel	=	0.315	+	0.815 (duff wt)	-	0.215 (wind)	+	0.410 (1000 h wt)			0.916

[1] wt = weight in kilograms/square meter.
[2] wind = effective wind speed (vector of slope and wind)
[3] temp = temperature in degrees Centigrade
[4] fac = weight (kg/m^2)/moisture content (decimal fraction)
[5] rh = relative humidity (decimal fraction)
[6] hour wood refers to the equilibrium moisture content timelags with the atmosphere
1 hour woody = 0.0 - 0.635 cm d woody piece (0.0 - ¼ in d)
10 hour woody = 0.635 - 2.54 cm d woody piece (¼ in - 1 in d)
100 hour woody = 2.54 - 7.62 cm d woody piece (1 - 3 in d)
1000 hour woody = > 7.62 cm d woody piece (> 3 in d)

Table 29. Models for reduction of individual and combined fuels (kg/m^2) for backfires. All independent variables are preburn measurements.

Y^6	=	B_0	+	B_1 (X_1)	+	B_2 (X_2)	+	B_3 (X_3)	+	B_4 (X_4)	R^2
Individual fuels											
Litter	=	-0.0678	+	0.130 (litter fac)[1]							0.659
Duff	=	-1.85	+	0.302 (duff wt)[2]	+	2.92 (1 h fac)	+	0.521 (wind)[3]			0.750
1 hour woody	=	-0.0050	+	0.949 (1 h wt)	+	0.0012 (temp/rh)[4]	-	0.0082 (1/1 h mc)[5]			0.904
10 hour woody	=	-0.0245	+	0.827 (10 h wt)							0.805
100 hour woody	=	-0.0156	+	0.243 (100 h wt)	+	0.203 (herb fac)	+	0.150 (shrub wt)	-	0.0042 (wind)	0.867
1000 hour woody	=	1.16	+	0.402 (1000 h wt)	-	7.41 (100 h wt)	-	0.381 (10 h fac)	-	0.295 (wind)	0.859
Combined fuels											
Litter-duff	=	-2.00	+	4.39 (1 h fac)	+	0.666 (wind)	+	8.42 (100 h wt)			0.749
Total woody	=	0.208	+	0.356 (1000 h wt)	-	6.92 (100 h wt)					0.742
Total fuel	=	-0.970	+	0.552 (100 h wt)	+	4.90 (1 h fac)	-	1.07 (10 h fac)	+	0.601 (litter fac)	0.812

[1] fac = weight (kg/m^2)/moisture content (decimal fraction)
[2] wt = weight in kilograms/square meter
[3] wind = effective wind speed (vector of slope and wind)
[4] temp = temperature in degrees Centigrade
rh - relative humidity (decimal fraction)
[5] mc = moisture content (decimal fraction)
[6] hour wood refers to the equilibrium moisture content timelags with the atmosphere
1 hour woody = 0.0 - 0.635 cm d woody piece (0.0 - ¼ in d)
10 hour woody = 0.635 - 2.54 cm d woody piece (¼ in - 1 in d)
100 hour woody = 2.54 - 7.63 cm d woody piece (1 - 3 in d)
1000 hour woody = > 7.62 cm d woody piece (> 3 in d)

reduce fuel loading, which is related to fuel amount and moisture content, and limit the crown scorch, which is related to temperature, relative humidity, and wind.

Land managers have some control over fuel loading by ranking their forest stands on the basis of fuel's management need. Once the decision has been made to burn a stand, the land managers' control over fuel moisture and weather conditions rests with timing of the ignition. The following conditions are suggested for fuel reduction in a stand of mature ponderosa pine/Douglas-fir:

Fuel moisture:	litter	9 - 11%
	1-h woody	9 - 11%
	10-h woody	10 - 13%
	duff	15 - 25%
	herbaceous	< 75%
Weather:	effective wind speed	3 - 6 kph (2-4 mph)
	air component	20 - 125
	provided temperature	> 0°
	and rh is between	20 - 60%

Sampling

The Planar Intersect Method (PIM) of woody fuel sampling (Brown 1974) was found to be inadequate in both design and application to prescribed understory burning. First, the 1 h and 10 h woody fuel loadings as estimated by the PIM were poorly correlated to the direct weight sampling by 0.1 square meter quadrat (R^2 = .002 and .092, respectively (Appendix H). Second, in the Planar Intersect Method, the 1000 h woody fuel pieces were classified as duff if the center of the piece was beneath the upper surface of the duff. However, sound 1000 h fuel pieces had a greater density than the surrounding duff. These fuels did not respond in the same manner to changes in the microclimate (temperature and weather), nor did they have the same ignitability.

Hence, cool understory burning frequently removed much of the low density duff, but left the sound 1000 h pieces intact. These woody pieces were not counted preburn, were exposed, and may have been counted postburn. This erroneously resulted in a net increase in the 1000 h fuel loading from application of prescribed fire. A third design problem involved detection of woody fuel load reduction by this method. Woody fuel particle might have lost weight by pyrolysis without changing size in incomplete combustion (Brown 1972). The tally system for the 1, 10, and 100 h fuels in the PIM might not have detected this weight change. Partial consumption of a woody piece might have reduced its size, placing the piece into a smaller postburn sampling category. This introduced sampling error into the fuel reduction of all woody categories less than 7.63 cm. Several procedures needed to be employed to correct these design flaws. First, the PIM should not be used to sample material less than 2.54 cm d. Instead, direct weight samples should be used. Second, all sound, buried woody pieces greater than 7.62 cm d which intersect the transect line should be counted as sound 1000 h preburn and postburn fuel. Nothing can be changed in sampling procedure to correct partial combustion size changes in the woody pieces except to estimate the magnitude of this error.

Application of the PIM in this study had some shortcomings. First, permanent transects were unacceptable. Any disturbance of the woody fuel pieces between preburn and postburn sampling affected the postburn measurements. This introduced sampling error which confounded the fire effects analysis. Second, the sampling plane used was too short (50 ft), which resulted in many "zero" tallies, leading to a high standard deviation for preburn and postburn fuel loading. These

problems are correctable by systematically or randomly placing numerous long temporary transects, both preburn and postburn, in each experimental unit.

Efficiency of sampling can be improved in two areas. The 0.1 square meter Daubenmire Quadrat (Daubenmire and Daubenmire 1980) should be replaced with a 0.1 square meter circular subplot. The 20% reduction in the circumference brought about through this change would mean fewer decisions concerning borderline fuels and vegetation, which would reduce the time per plot and increase the precision. The nested belt transect could also be changed to a circular shape of the same area (Figure 2).

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APPENDIX A

Duff moisture content trend at Worley and Plummer units during the burning period.

Source	df	Sum of Squares	F Value	
Day	1	.09286194	29.01	.0001
Error	23	.07362880		
Total	24	.16649074		

Duff moisture content (dec. frac.) = .4136 - .00670 (burning day)

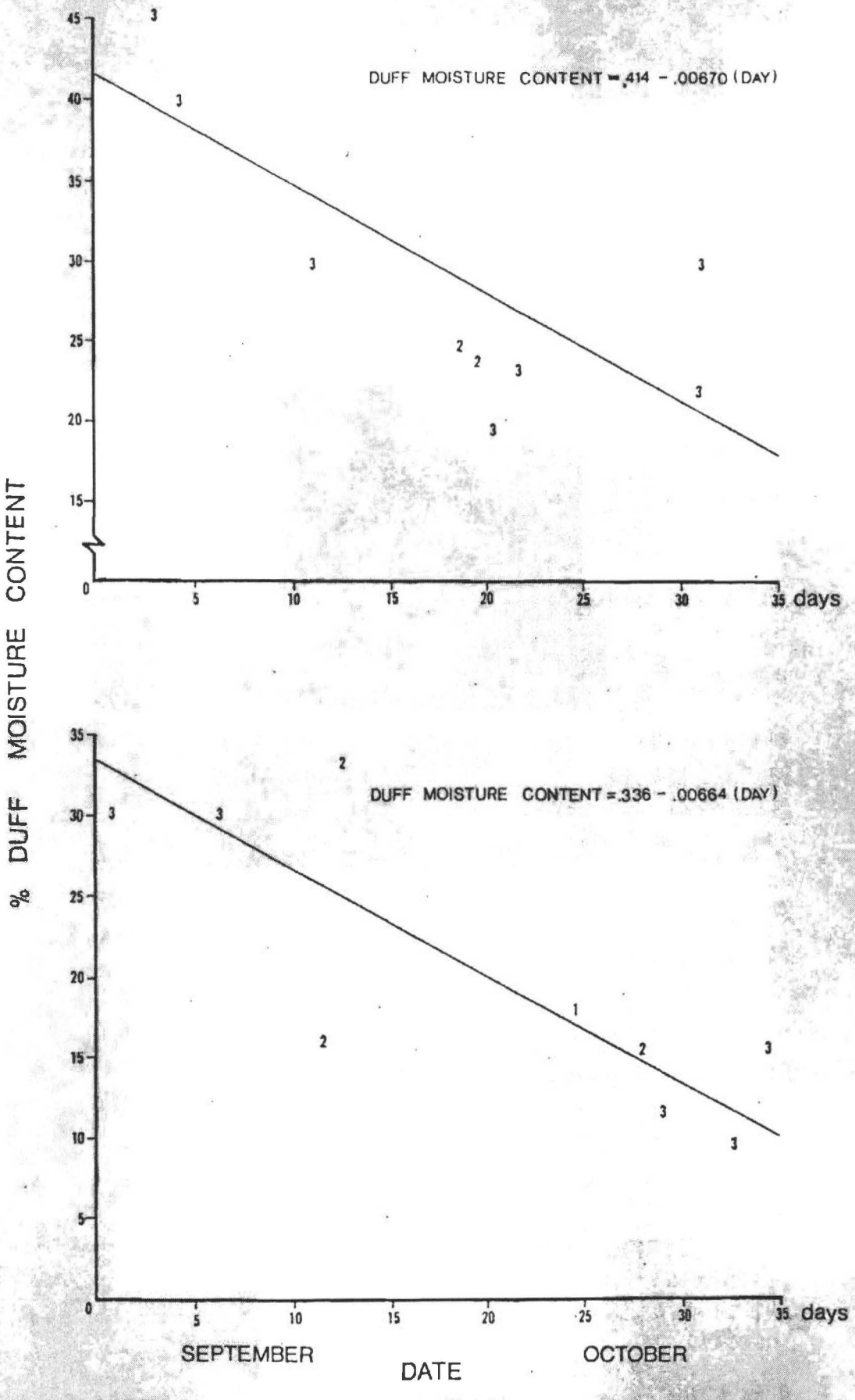
R^2 = .558
p F = .0001

Duff moisture content trend at Tensed units during the burning period.

Source	df	Sum of Squares	F Value	
Day	1	.13546080	53.75	.0001
Error	21	.05292581		
Total	22	.18838661		

Duff moisture content (dec. frac.) = .3361 - .00664 (burning day)

R^2 = .719
p F = .0001


DUFF MOISTURE CONTENT = .414 - .00670 (DAY)
DUFF MOISTURE CONTENT = .336 - .00664 (DAY)
% DUFF MOISTURE CONTENT
days
SEPTEMBER
OCTOBER
DATE

APPENDIX B

Fire behavior variable means by location including scorch height, flame residence time, rate of fire spread, and flame length.

LOCATION	SCORCH HEIGHT 1/ (m)	RESIDENCE TIME (s)	RATE OF FIRE SPREAD (m/min)	FLAME LENGTH (m)
PLUMMER	4.51 a 2/	20.7 a	1.326 a	.621 a
WORLEY	5.61 a	24.9 a	.945 a	.380 a
TENSED 1	5.80 a	2.53 a	.933 a	.479 a
TENSED 2	3.65 a	16.6 a	.856 a	.418 a

1/ Means are corrected for by the covariant - duff fuel component.

2/ Means in the same column followed by the same letter are not significantly different at $p \leq .05$.

APPENDIX C

Total fuel reduction (kg/m^2) - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	16.62278645	4.88	.0051
Burn Type	3	57.10801541	16.77	.0001
Loc * Type	9	9.40975242	.92	.5164
Duff_fac	1	11.90939107	10.49	.0023
Error	44	49.95794015		
Total	60	158.65954270		

Litter Reduction ($kg.m^2$) - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.04340749	.72	.5457
Burn Type	3	1.22465623	20.35	.0001
Loc * Type	9	.10177622	.56	.8190
Duff_fac	1	.04876545	2.43	.1261
Error	44	.88272270		
Total	60	2.32110889		

Duff Reduction (kg/m^2) - Analysis of covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	12.03985852	5.18	.0038
Burn Type	3	23.80491205	10.24	.0001
Loc * Type	9	5.69711598	.82	.6038
Duff_fac	1	10.13534907	13.08	.0008
Error	44	34.10573887		
Total	60	94.70929464		

0.0 - .635 cm d woody fuel reduction (kg/m^2) - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.00304975	.91	.4418
Burn Type	3	.01425875	4.27	.0099
Loc * Type	9	.00264331	.26	.9810
Duff_fac	1	.00493915	4.44	.0408
Error	44	.04892424		
Total	60	.07985476		

.635 - 2.54 cm d woody fuel reduction (kg/m^2) - Analysis of covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.01942249	.60	.6184
Burn Type	3	.13492041	4.17	.0111
Loc * Type	9	.08201731	.84	.5799
Duff_fac	1	.02565538	2.38	.1302
Error	44	.47475923		
Total	60	.73615397		

2.54 - 7.62 cm d woody fuel reduction (kg/m^2) - Analysis of covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.00227641	.86	.4677
Burn Type	3	.01165470	4.42	.0085
Loc * Type	9	.01005348	1.27	.2802
Duff_fac	1	.00003066	.03	.8528
Error	44	.03871448		
Total	60	.06262193		

> 7.62 cm d woody fuel reduction (kg/m^2) - Analysis of covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.62658456	.66	.5809
Burn Type	3	1.34108284	1.41	.2516
Loc * Type	9	3.34303694	1.17	.3347
Duff_fac	1	.03588225	.11	.7379
Error	44	13.91752084		
Total	60	19.57266730		

APPENDIX D

Flame length - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	.50866875	4.03	.0130
Burn Type	3	7.03278428	55.70	.0001
Loc * Type	9	.38435885	1.01	.4436
Duff_fac	1	.06481978	1.54	.2213
Error	43	1.80964959		
Total	59	10.04913947		

Rate of fire spread (m/m) - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	1.98963598	.79	.5071
Burn Type	3	46.46570326	18.41	.0001
Loc * Type	9	8.00980944	1.06	.4126
Duff_fac	1	2.97969126	3.54	.0668
Error	42	35.32626438		
Total	58	97.12964806		

Scorch height (m) - Analysis of covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	34.31205574	.68	.5717
Burn Type	3	724.93330476	14.33	.0001
Loc * Type	9	90.74294890	.60	.7890
Duff_fac	1	46.42527265	2.75	.1068
Error	32	539.53572877		
Total	48	1486.31307397		

APPENDIX E

Analysis of variance of the percent of the area distrubed. Model includes the locations, the three burn treatments, and the location-treatment interaction.

Source	df	Sum of Squares	F Value	Alpha
Location	3	337.59913539	.33	.8036
Treatment	2	402.79242096	.59	.5592
Loc * Trt	6	1443.88097730	.71	.6469
Error	36	12273.74827982		
Corrected Total	47	14458.02081342		

APPENDIX F

Analysis of covariance of the percent of the area blackened by fire. The model includes the location, the three burn treatments, the location-treatment interaction, and the covariant, the percent of the area disturbed.

Source	df	Sum of Squares	F Value	Alpha	
Location	3	1325.73586819	1.50	.2319	
Treatment	2	781.07338181	1.32	.2789	
Loc * Trt	6	1566.02376591	.89	.5160	
Disturb	1	1768.09604824	6.00	.0195	*
Error	35	10319.10253805			
Corrected Total	47	15760.03160219			

* Significant at $\alpha \leq .05$ level.

Residence time(s) - Analysis of Covariance

Source	df	Sum of Squares	F Value	Alpha
Location	3	676.61773211	2.59	.0649
Burn Type	3	10182.95654055	39.02	.0001
Loc * Type	9	444.36706078	.57	.8158
Duff_fac	1	720.57972845	8.28	.0062
Error	43	3740.61008637		
Total	59	16554.49259259		

APPENDIX G

Ladder effect
Backfire

Source	df	Sum of Squares	F Value	α
Slash	1	23.88304934	2.55	.114
Shrubs	1	35.06748781	3.74	.056
Density	1	30.53819240	3.26	.074
Flame	1	94.53666991	10.09	.002
Error	97	908.88636524		
Total	101	1092.91176471		

R^2 = .168

p F = .0012

Free-running headfires

Source	df	Sum of Squares	F Value	α
Slash	1	372.47518911	9.99	.002
Shrubs	1	41.63816007	1.12	.292
Density	1	84.53758377	2.27	.134
Flame	1	308.23108188	8.27	.005
Error	136	5069.85557382		
Total	140	5876.73758865		

R^2 = .137

p F = .0004

Strip headfires

Source	df	Sum of Squares	F Value	∝
Slash	1	2.73851586	.08	.774
Shrubs	1	6.00334453	.18	.671
Density	1	0.00052655	.00	.997
Flame	1	17.82165263	.54	.464
Error	133	4392.34175752		
Total	137	4418.90579710		

$R^2 = .006$

p F = .9374

APPENDIX H

Comparison measuring of 1 hour woody fuels by quadrat and Planar Intersect Method - Analysis of Variance

Source	df	Sum of Squares	F Value	Alpha
Model	1	.00045062	.11	.7379
Error	46	.18288455		
Total	47	.18333517		

Preburn 1 h fuel weight = .0597 - .0949 (preburn 1 h fuel weight Planar Intersect Method)
quadrat

R2 = .0024

Comparison measuring 10 hour woody fuels by quadrat and Planar Intersect Method - Analysis of Variance

Source	df	Sum of Squares	F Value	Alpha
Moded	1	.36290036	4.69	.0356
Error	46	3.56179087		
Total	47	3.92469123		

Preburn 10 hour fuel weight = .0733 + .251 (preburn 10 h fuel weight Planar Intersect Method)
Quadrat

R^2 = .092

APPENDIX I

Fuel accumulations (kg/m^2) of litter, 1 h (0-.635 cm d) and 10 h (.635-2.54 cm d) at each location between October 1978 and June 1979.

FUEL	TENSED 1	TENSED 2	WORLEY	PLUMMER
Litter	.111	.162	.216	.230
1 h	.040	.021	.031	.038
10 h	.027	.003	.082	.077